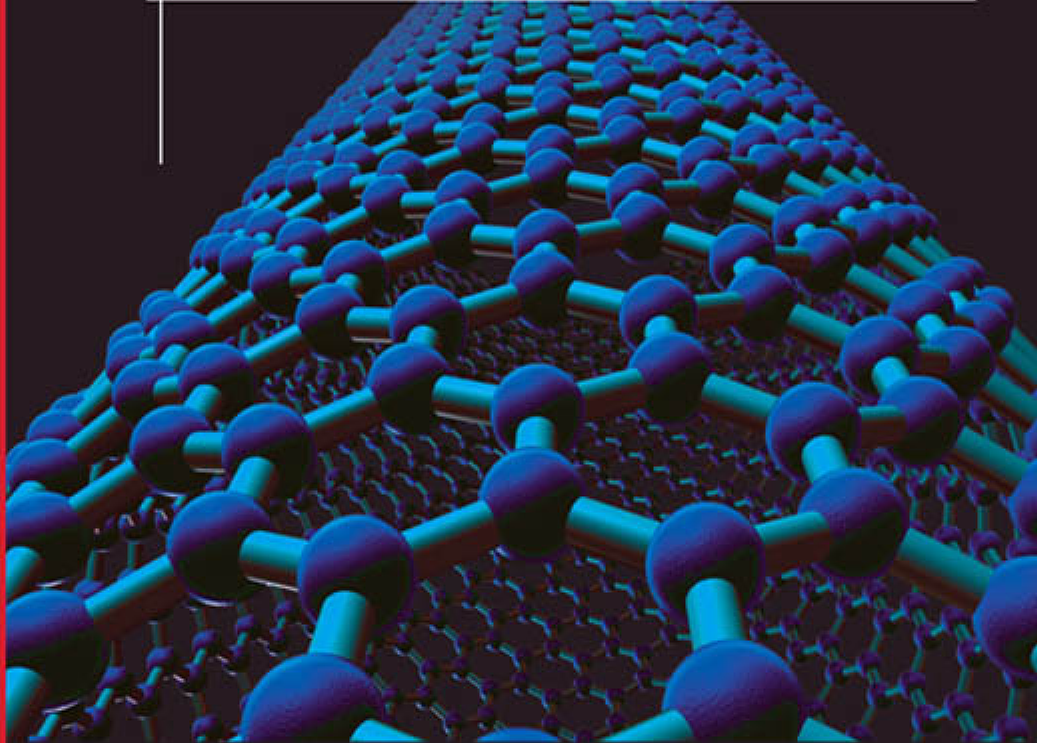
McGraw-Hill Nanoscience and Technology Series

MEMS/MOEMS PACKAGING

CONCEPTS, DESIGNS, MATERIALS, AND PROCESSES



KEN GILLEO

MEMS/MOEMS Packaging

McGraw-Hill Nanoscience and Technology Series
Series Editor: Omar Manasreh

GILLEO • *MEMS/MOEMS Packaging*
LOBONTIU • *Mechanical Design of Microresonators*
PETERS • *Molecular Thermodynamics and Transport Phenomena*

MEMS/MOEMS Packaging

Concepts, Designs, Materials, and Processes

Ken Gilleo, Ph.D.

ET-Trends LLC
Warwick, Rhode Island

McGraw-Hill

New York Chicago San Francisco Lisbon London Madrid
Mexico City Milan New Delhi San Juan Seoul
Singapore Sydney Toronto

The McGraw-Hill Companies

Copyright © 2005 by The McGraw-Hill Companies, Inc. All rights reserved. Manufactured in the United States of America. Except as permitted under the United States Copyright Act of 1976, no part of this publication may be reproduced or distributed in any form or by any means, or stored in a database or retrieval system, without the prior written permission of the publisher.

0-07-158909-0

The material in this eBook also appears in the print version of this title: 0-07-145556-6.

All trademarks are trademarks of their respective owners. Rather than put a trademark symbol after every occurrence of a trademarked name, we use names in an editorial fashion only, and to the benefit of the trademark owner, with no intention of infringement of the trademark. Where such designations appear in this book, they have been printed with initial caps.

McGraw-Hill eBooks are available at special quantity discounts to use as premiums and sales promotions, or for use in corporate training programs. For more information, please contact George Hoare, Special Sales, at george_hoare@mcgraw-hill.com or (212) 904-4069.

TERMS OF USE

This is a copyrighted work and The McGraw-Hill Companies, Inc. ("McGraw-Hill") and its licensors reserve all rights in and to the work. Use of this work is subject to these terms. Except as permitted under the Copyright Act of 1976 and the right to store and retrieve one copy of the work, you may not decompile, disassemble, reverse engineer, reproduce, modify, create derivative works based upon, transmit, distribute, disseminate, sell, publish or sublicense the work or any part of it without McGraw-Hill's prior consent. You may use the work for your own noncommercial and personal use; any other use of the work is strictly prohibited. Your right to use the work may be terminated if you fail to comply with these terms.

THE WORK IS PROVIDED "AS IS." McGRAW-HILL AND ITS LICENSORS MAKE NO GUARANTEES OR WARRANTIES AS TO THE ACCURACY, ADEQUACY OR COMPLETENESS OF OR RESULTS TO BE OBTAINED FROM USING THE WORK, INCLUDING ANY INFORMATION THAT CAN BE ACCESSED THROUGH THE WORK VIA HYPERLINK OR OTHERWISE, AND EXPRESSLY DISCLAIM ANY WARRANTY, EXPRESS OR IMPLIED, INCLUDING BUT NOT LIMITED TO IMPLIED WARRANTIES OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE. McGraw-Hill and its licensors do not warrant or guarantee that the functions contained in the work will meet your requirements or that its operation will be uninterrupted or error free. Neither McGraw-Hill nor its licensors shall be liable to you or anyone else for any inaccuracy, error or omission, regardless of cause, in the work or for any damages resulting therefrom. McGraw-Hill has no responsibility for the content of any information accessed through the work. Under no circumstances shall McGraw-Hill and/or its licensors be liable for any indirect, incidental, special, punitive, consequential or similar damages that result from the use of or inability to use the work, even if any of them has been advised of the possibility of such damages. This limitation of liability shall apply to any claim or cause whatsoever whether such claim or cause arises in contract, tort or otherwise.

DOI: 10.1036/0071455566

Want to learn more?

We hope you enjoy this McGraw-Hill eBook! If you'd like more information about this book, its author, or related books and websites, please click here.

This book is dedicated to the spirit of teamwork and cooperation in the amazing field of MEMS, which is becoming the center of convergence for all sciences and technologies.

This page intentionally left blank

For more information about this title, click here

Contents

Preface xi

Chapter 1. Engineering Fundamentals of MEMS and MOEMS Electronic Packaging 1

1.1 The Package as the Vital Bridge 2
1.2 Packaging Challenges 3
1.3 Multiple Functions 7
1.3.1 Protection 7
1.3.2 Connectivity 8
1.3.3 Compatibility; chip-to-package 11
1.3.4 Compatibility; package-to-printed circuits 13
1.3.5 Routing 14
1.3.6 Electronic routing 15
1.3.7 Materials routing 15
1.3.8 Mechanical stress control 16
1.3.9 Thermal management 17
1.3.10 Assembly simplification 17
1.3.11 Performance enhancement 18
1.3.12 Testability and burn-in 18
1.3.13 Removability and reworkability 18
1.3.14 Standardization 19
1.4 Package Types 19
1.4.1 Fully hermetic packages 19
1.4.2 Nonhermetic plastic 23
1.4.3 Overmolding capped devices 25
1.4.4 Near-hermetic package—a new class 26
1.5 Reliability and Qualification 27
1.6 Summary 28

Chapter 2. Principles, Materials, and Fabrication of MEMS and MOEMS Devices 29

2.1 Definitions and Classifications 31
2.2 Basic Principles 33
2.3 Sensing 34

2.4 MEMS Sensor Principles 35
2.4.1 Inertial (motion) sensors 35
2.4.2 Pressure sensors 37
2.4.3 Chemical sensors 38
2.5 Motion Actuation 39
2.6 MEMS "Engines" 40
2.6.1 Electrostatic/capacitance 40
2.6.2 Electromagnetic actuators 42
2.6.3 Bimorphic actuators 42
2.6.4 Piezoelectric actuators 43
2.6.5 Other actuators 43
2.7 CAD Structure Library; Building Blocks 44
2.7.1 Device materials 44
2.7.2 Fabrication methods and strategies 45
2.8 MEMS Devices 46
2.8.1 Sensors 47
2.8.2 Controllers 48
2.9 Optical-MEMS; MOEMS 49
2.10 Intelligent MEMS 49
2.11 MEMS Applications 50
2.11.1 MEMS sensors; endless applications 50
2.12 MOEMS Devices—MEMS Plus Light 58
2.12.1 Light control principles 58
2.12.2 Applications for optical MEMS (MOEMS) 59
2.13 Summary 63

Chapter 3. MEMS and MOEMS Packaging Challenges and Strategies 65

3.1 Product-Specific Character of MEMS Packaging 65
3.2 MEMS General Packaging Requirements 66
3.2.1 Free space (gas, vacuum, or fluid) 66
3.2.2 Free space (fluid) 69
3.2.3 Low contamination 70
3.2.4 Minimal stress 71
3.2.5 Temperature limitations 72
3.2.6 In-package environmental control 73
3.2.7 Selective access to outside 74
3.2.8 Mechanical shock limits 75
3.2.9 Stiction 76
3.2.10 RF shielding 77
3.2.11 Fluidics management 77
3.2.12 High-vacuum enclosures 79
3.2.13 Device as the package 79
3.2.14 Cost 79
3.3 Hermeticity; Levels, Evaluation Methods, and Requirements; Perceived versus Actual 80
3.4 Cost versus Performance Trade-offs 82
3.5 Emergence of Low-Cost Near-Hermetic Packaging 82
3.5.1 Definition and description 82
3.5.2 Material choices 83
3.5.3 Interconnect schemes 84

3.6 Manufacturing Process Comparisons 84
3.6.1 Metal packages 84
3.6.2 Ceramic packages 86
3.6.3 Plastic packages: plastic versus ceramic 90
3.6.4 Chip assembly in plastic packages 103
3.6.5 Lid sealing 103
3.6.6 Package barrier issues 105
3.6.7 Hermeticity testing of injection molded packages 106
3.6.8 Package enhancement 108
3.6.9 Productivity using strips and arrays 110
3.6.10 Acceptance of NHP molded package technology 111
3.6.11 Status of NHP and MEMS-specific packaging 111
3.7 The Packaging MOEMS (Optical-MEMS)—Additional Requirements 112
3.7.1 Windows and ports 112
3.7.2 Maintaining optical clarity 115
3.7.3 Dimensional stability 115
3.7.4 Thermal management 115
3.7.5 In-package dynamic alignment 116
3.8 Packages for Materials Handling 116
3.8.1 Design concepts 117
3.8.2 Fluidic systems 117
3.8.3 Gas/airborne agent analyzers 117
3.8.4 Nanoscale particles and MEMS 118
3.8.5 Selectivity for ports 118
3.9 NHP Beyond MEMS 118

Chapter 4. MEMS Packaging Processes 121

4.1 Release Step 123
4.1.1 Stiction and cleaning 125
4.2 Singulation; Sawing and Protection 126
4.3 Capping Approaches 128
4.3.1 Dielectric caps 129
4.3.2 Caps with first-level interconnects 130
4.3.3 Caps with second-level interconnects 131
4.4 Die Attach 133
4.5 Wire Bonding 133
4.6 Flip Chip Methods 133
4.7 Tape Automated Bonding 136
4.8 Selective Underfill and Encapsulation 139
4.9 Lid Sealing 139
4.9.1 Thermal adhesive application 140
4.9.2 UV curing of sealants 141
4.9.3 Laser sealing 142
4.9.4 Ultrasonic sealing 144
4.9.5 Direct heat bonding 145
4.9.6 RF sealing/welding 145
4.9.7 Electric welding 146
4.9.8 Mechanical locking 146
4.9.9 Soldering 146
4.9.10 Brazing 146
4.9.11 Hinged-to-package lids 147

4.10 Antistiction Processes 148
4.11 In-Process Handling 151
4.12 Applying In-Package Additives 151
4.12.1 Getters application processes 151
4.12.2 Lubricant application 152
4.13 Equipment 152
4.14 Testing 152
4.15 Reliability 152
4.15.1 Contamination effects 153
4.16 Selecting the Right MEMS/MOEMS Package and Materials 154
4.16.1 The process cost overkill 154
4.17 Conclusions and Summary 155

Chapter 5. MEMS Packaging Materials 159

5.1 The Process Determines the Materials 159
5.1.1 Electrically conductive materials—interconnects 160
5.1.2 Surface finishes for metals 162
5.1.3 Enclosure materials 163
5.1.4 Organic plastics and their benefits 164
5.1.5 Epoxy limitations 167
5.1.6 Metals versus ceramics versus plastics 168
5.2 Joining Materials 171
5.3 Assembly Issues and Material Solutions 172
5.3.1 Protection during singulation 172
5.3.2 Die attach adhesives 173
5.3.3 Lid seal materials 174
5.4 In-Package Additives 174
5.4.1 Getters 175
5.4.2 Humidity control agents 177
5.4.3 Antistiction agents 178
5.4.4 Lubricants/antiwear agents 179
5.5 Conclusions 181

Chapter 6. From MEMS and MOEMS to Nanotechnology 183

6.1 Definitions Are Important 186
6.2 Combining Nano and MEMS 189
6.2.1 Nanomaterials added to MEMS and MOEMS devices 189
6.2.2 MEMS to handle nanomaterials 190
6.2.3 Nanocomponents for MEMS 190
6.2.4 Nanomeasurement 191
6.2.5 Nanodevices 192
6.2.6 Nanoelectronics devices 193
6.2.7 Nanoelectronics plus MEM 198
6.2.8 Nano enhanced packaging 198
6.3 Packaging Nano 200
6.4 Summary, Conclusions, and the Future 201

Bibliography 203
Index 215

Preface

MEMS may well become a hallmark technology for the 21st century. The capability to sense, analyze, compute and control, all within a single chip, will provide new and powerful products during this decade and far beyond. MEMS deals with the integration of everything from motion, light, sound, molecular detection, radio waves to computation. While sensors are a large and expanding market, MEMS also brings control—electrical, mechanical, optical, fluidic, electromagnetic, and more. Merging of motion, sensing, control and computation within a very compact single system is a major leap in technology. Although there are still challenges ahead, there are no remaining problems without impending solutions. MEMS is the vital enabler where convergence of technology and science will miniaturize and unite mechanics, electronics, optics, and all other vital areas including chemistry, physics, biology, and medicine. Continued technical success is assured at the device level because MEMS is a robust and well-supported member of the huge semiconductor industry. Worldwide electronic giants, innovative start-ups, government laboratories, and hundreds of universities are strongly supporting this most valuable technology group of the 21st century.

Today, MEMS is on a solid, healthy, and accelerating growth curve after many years of hard work with high expectations. Many technology watchers recognized that MEMS was a very important field, but few realized the broad scope and extreme versatility that could be developed. The emerging view of MEMS is that it is the synergistic addition of "mechanics, motion, and light (MOEMS)" to existing electronic semiconductor devices and a focal point for the convergence of almost all of the sciences; every technology can benefit and many will be boosted significantly. Since mechanics, photonics, and electronics are already so intertwined at the macro-level, MEMS is being viewed by the electronics industry as an enhanced electronic-based device platform that can become as pervasive as the computer chip. There are already more than 250 commercial MEMS companies actively working in this field, including well-established companies like Agilent, Analog Devices, Canon, Delphi, Denso, Epson, GE

Copyright © 2005 by The McGraw-Hill Companies, Inc. Click here for terms of use.

Infrastructure Sensing, Hewlett Packard, Honeywell, IBM, Intel, Kavilico, Lexmark, Motorola (Freescale), Robert Bosch, ST Microdevices, Texas Instruments, and VTI Technology. Major professional organizations have endeavored to become important MEMS resource centers. Most industrialized countries now have major government programs in MEMS. The U.S. government continues to expand MEMS development and capability primarily through Sandia National Laboratories, especially in areas that are dedicated to defense and national security; MEMS devices are now critical components for defense and security. Other active laboratories include CEA-LETI, Fraunhofer, and IMEC. Nearly every university is doing MEMS research and several are now offering MEMS engineering degrees.

But there are challenges. While much success has been achieved at the device level, packaging has lagged behind. Very little funding has been provided for package development, perhaps because of the erroneous assumption that existing technology would suffice. Most packaging experts feel that MEMS package design and manufacturing represents the greatest challenge ever for their industry. Not only are the newest MEMS devices small and complex, they must often communicate with the outside world by modes beyond just electrical input/output. The exception is motion-sensing devices like accelerometers and gyroscopes that only need electrical connections. Since these sensor chips can be capped at wafer-level, a topic covered in this book, many can be overmolded but with diminished sensitivity due to encapsulant shrinkage and stress. Since these mature MEMS products have been well publicized, many have incorrectly concluded that MEMS packaging is also established. How wrong! A packaging solution for an air bag accelerometer offers no solutions for a BioMEMS system or an air-measuring hazards sensor. Advanced MEMS, and perhaps all MOEMS chips, will require cavity type packaging and cannot generally use the overmolding process employed for most inertial sensors.

The traditional packaging strategy seeks to keep everything away from the device, except electrical power and signal. The most common electronic package, the non-hermetic plastic type, requires encapsulation materials to directly contact the chip. But the mechanical character of MEMS precludes the use of epoxy overmolding and other standard packaging processes. However, this book describes wafer-level protection schemes that may allow modified standard packaging processes to be used, including some for optical-MEMS chips. But when a cavity is essential, the MEMS specialist is left with a very limited choice of package designs, and those that can be used are not cost-effective. The forced use of overly expensive hermetic packages that were designed for military electronics and specialty telecommunications products has been detrimental. While packaging costs for electronics make up only 4 to 5 percent of the total, the MEMS package has been more costly than the

device inside. Packaging costs that make up 50 to 80 percent of the product have held back the growth of MEMS by precluding some of the attractive markets that are cost-sensitive. This book offers alternatives.

The goal of this practical book is to help MEMS crafters and technologists step out of the "box" of traditional, but expensive packaging that might otherwise become the "coffin" that buries a great idea. It is absolutely essential that MEMS and MOEMS packaging moves onto a new plateau of innovation with designs specifically for these mechanical and optical devices that are so different from anything that came before. MEMS devices, especially for volume commercial applications, must not be constrained by cost and performance limitations of "off the shelf—but doesn't quite fit" products. This book methodically covers packaging principles, designs, materials, and processes. New concepts, such as the *near-hermetic package* (NHP), are introduced and discussed in detail. Thermoplastic injection molding, ideal for low-cost mass-production of cavity packages, is thoroughly described. Many new packaging ideas are presented that are intended to stimulate new approaches within this field. MEMS packaging innovation will also pave the way for *nanoelectromechanical systems* (NEMS). Nanotechnology is already being applied to MEMS products and these two powerful technologies will move closer together over time. The tools required and being developed for MEMS are the most versatile yet proposed for unconventional devices and can serve as a launch pad for nanotechnology in the future.

Ken Gilleo, Ph.D.

This page intentionally left blank

MEMS/MOEMS Packaging

This page intentionally left blank

Chapter

1

Engineering Fundamentals of MEMS and MOEMS Electronic Packaging

The electronic component package that began as a simple glass enclosure for radio vacuum tubes has evolved into a sophisticated system that is now the nucleus of a new era of technology advancement. Packaging is undergoing one more revolution, perhaps even the last, when viewed from several perspectives. Integrated circuits (ICs) continue to grow more complex and to operate at ever-higher speeds while chip dimensions get smaller as the industry perpetually pursues Moore's law, which predicts the doubling of performance every 18 months. The package must accommodate these changes in electronic devices that create an escalating challenge for connecting to printed circuit boards that evolve and advance much more slowly than semiconductors. The package is in the midst of transitioning from chip-scale to exponentially higher density multichip systems. Vertically stacked *three-dimensional* (3D) package designs are finally gaining success and now being used in most of the latest mobile phones. Some feel that 3D stacking is the final revolution in densification because this scheme produces a cubelike, volume-maximized, footprint-minimized package. This may be true for today's silicon-based electronic devices, but many new devices, including those based on Nanotechnology, are on the horizon and others are already here, like *microelectromechanical systems* (MEMS) and *micro-optoelectromechanical systems* (MOEMS).

Today, the myriad of mechanical and optomechanical devices urgently need the right package—one that may not yet exist for many of the chip designs. MEMS devices present the newest and most intriguing set of

Copyright © 2005 by The McGraw-Hill Companies, Inc. Click here for terms of use.

challenges for packaging developers and manufacturers. This chapter will begin by detailing and discussing the various elements and functions of the electronic package and then move to the task of identifying the unique requirements for *mechanical* chips. We will examine the most important general functions and features of the generic package before moving to the more specialized requirements for MEMS and MOEMS.

1.1 The Package as the Vital Bridge

The package may appear to be just a tiny black plastic box, gray stone-like slab, or a bright metal container that is used to hold the chip, but it is actually a sophisticated system when we carefully examine the tasks that must be accomplished under extreme and varying conditions. The package continues to be the *bridge* between the contrasting industries of semiconductors and *printed circuit boards* (PCBs). But as the chasm between chips and PCBs grows wider, the package designers' mission grows larger. Some package attributes are absolutely essential, others are beneficial, and still others are product-specific that may have no precedent. Essential requirements include providing the electrical interconnect system between the tiny semiconductor and larger scale PCB. Signal routing is essential for some applications like *flip chip* (FC) but not in every case. The package is the physical scale translator that can make the ultrafine chip features compatible with any substrate assembly pad layout. Environmental protection is almost always a requirement, but it is product-specific, and ranges from minimal protection for highly passivated and robust chips to extreme for some MEMS, MOEMS, and *optoelectronic* (OE) devices that are sensitive to almost everything in the surrounding environment. The package can also provide compatibility between chips with metal pads that are typically not solderable and PCBs that commonly employ a solder joint interconnect. And just surviving lead-free solder assembly that now raises the processing temperature by 40°C or more, is heroic. Mechanical shock resistance for the package and its connection to the PCB is often an important newer requirement for portable products like cell phones. The package should also be removable and preferably, reworkable. The finished assembly must often withstand temperature and humidity extremes throughout its long life, which is no small task. Other package attributes include testability, standardization, ease of automatic handling, miniaturization, performance enhancement, and heat management. But MEMS will add considerably more in the way of requirements and some will create a paradox. Figure 1.1 shows the relationship between package elements and the main attributes.

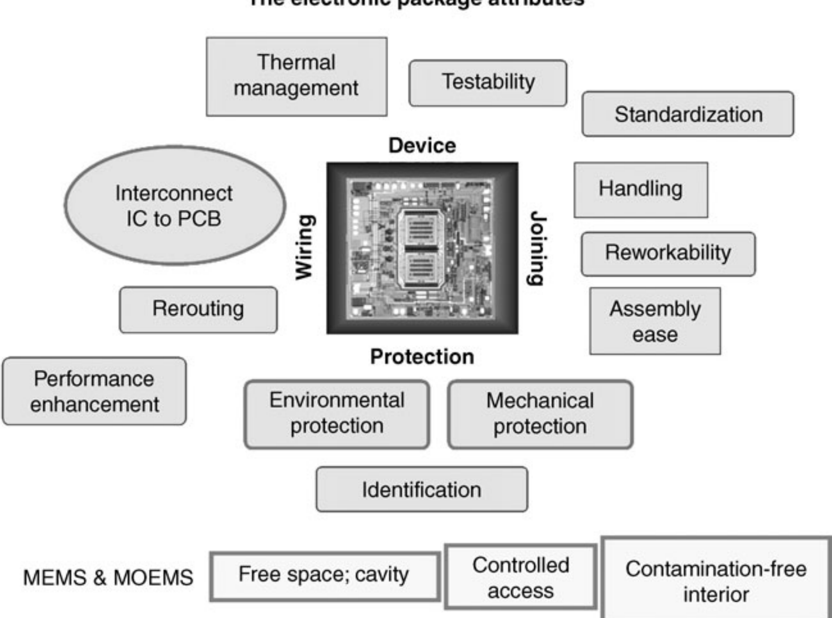


Figure 1.1 The package.

1.2 Packaging Challenges

In some ways, the component packaging industry is dynamic, but it also has enormous inertia that resists changes, especially those that can impact the long-established infrastructure. Design change often seems to run rampant so that too many package styles evolve, each with countless iteration. Even some of the *new* packages based on flexible circuitry materials can be traced back to products from the 1960s. New is old in most cases! Conversely, materials, especially for encapsulation, as well as their processes, have evolved slowly without real fundamental changes. The last important cost-cutting breakthrough for component packaging took place a half-century ago when the nonhermetic plastic package was successfully introduced. The DIP, or *dual in-line package*, became ubiquitous, and feedthrough assembly eventually became the *de facto* standard that still exists. But the DIP and other feedthrough packages eventually lost favor when a multitude of *surface mount technology* (SMT) packages were commercialized throughout the 1980s and the merits of surface mount assembly were confirmed. However, the early SMT designs were relatively simple modifications of the DIP pack. The metal leads could simply be bent outward into a “gull wing” shape that allowed the package to be bonded to metal pads on the surface of

the circuit board instead of pushing through holes in the board. Early electronic calculators from Texas Instruments used bent DIPs for surface mounting onto flexible circuits at least a decade before the SMT revolution began. And IBM used surface mount, *ball grid array* (BGA), *chip-scale packages* (CSPs) in the 1960s—decades before they were reinvented. Figure 1.2 shows the DIP.

The 1990s continued to advance SMT as the need to miniaturize while boosting lead count became important for continuing progress. The area array packaging revolution[1] gained momentum as the preferred solution for size reduction with concurrent increase in *input/output* (I/O) (number of package connections). This trend continues today and roadmaps show a continuation into the future. But moving to area array was an obvious solution to the problem of adding more and more leads to a smaller and smaller package. This "perimeter paralysis" was relieved by utilizing the readily available bottom of the package. However, the move to area array required many more changes than the switch from feedthrough to surface mount. The *metal lead frame* (MLF) that had been used for nearly all perimeter packages could not effectively support area interconnection. Chip carriers had to be developed that could serve as a platform for chip bonding but also provide an array of connection points on the bottom surface. This required true circuits with both dielectric and conductors. Although the *pin grid array* (PGA) was available, high-speed assembly demanded a solderable area array concept that led to the introduction of the BGA usually formed by attaching solder balls to the metal lands on the bottom of the package chip carrier. The BGA is becoming increasingly popular even though it is a more complex and costly package than the perimeter *surface mount device* (SMD). However, the BGA continues to evolve, but primarily to reduce cost. "No lead" or leadless versions are now in use like the *quad fine pitch no lead* (QFN) that has only metal pads on the bottom. Ironically, the new QFN-style package is a *land grid array* (LGA) concept that was used before the BGA-making

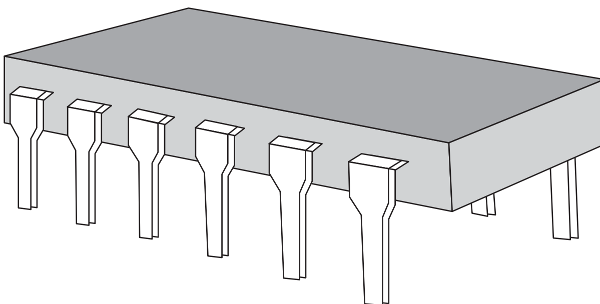
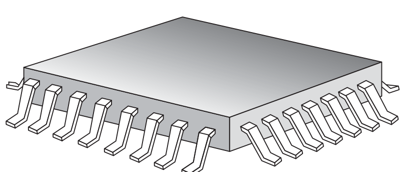


Figure 1.2 Dual in-line package.

progress, a step backwards. While solder bumps aid assembly, they are not necessary since solder paste must be screened onto PCB pads for other components. Solder paste is generally stenciled onto circuit boards using high-speed automated equipment. Figure 1.3 shows a leadframe quad pack SMD and a *plastic ball grid array* (PBGA) type package.

Electronic packaging has become an intensely energetic zone of technical development that is evolving ever faster as 3D stacked designs and *wafer level package* (WLP) processes are being implemented. The WLP is aimed at cost reduction by constructing the package on the semiconductor wafer, but some of the processes can produce unique results that are especially useful for MEMS devices and these concepts will be thoroughly described later. Now back to the issue of materials inertia.

While some of the new package designs are refreshingly novel, materials and the most basic manufacturing processes from past decades remain essentially unchanged. There are a few exceptions, of course, and most are in more specialized areas like flex-based packaging. Epoxies, used for over 50 years to mold plastic packages, are still the standard encapsulant for most of the newest designs even though this material class is plagued with intrinsic problems that are about to get worse. Epoxy, discovered in 1927, is still the "workhorse" polymer for most plastic packages.[2] But this could finally be changing. Thermoset *epoxy molding compounds* (EMCs) were once the obvious choice at a time when the plastic package was first developed. Epoxy resins were the right choice in the 1950s because they could withstand the heat of soldering and were easy to use. Epoxies are thermosets that once polymerized, don't remelt; they are permanently *set* as their name implies. Cross-links (chemical bonds) between polymer chains create a permanent 3D shape that cannot melt but can thermally decompose. The other broad class of polymers, remeltable thermoplastics, was not yet ready for high-temperature use in the 1950s and could not be a serious contender. Although epoxies have been favored by formulators for versatility and balanced properties, they are not considered to have any specific properties that are exceptional. But epoxies became part of the packaging industry's infrastructure, for better or for worse. Epoxies, like FR4, are also part of the printed circuit board infrastructure, but the industry is working



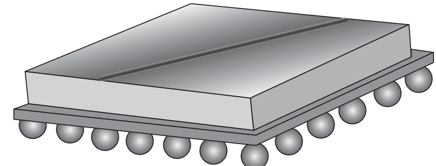


Figure 1.3 SMT quad pack and PBGA.

hard on alternative resin systems as lead-free soldering and halogen-free initiatives turn up the heat. And finally, the standard epoxy-transfer molding process is poorly suited for producing cavity-style packages that are needed for many types of MEMS devices.

Today, supply chain dynamics and aggressive outsourcing strategies are opening up a new and larger resource infrastructure that can offer newer materials and processes that have been successfully used by hundreds of industries. It's time to think outside the metal, ceramic, and epoxy boxes since the first two are priced higher and epoxy resins property and processing limitations are intrinsic. Pending regulations like *restriction of hazardous substances* (RoHS) in electrical and electronic equipment have restricted lead and are now aimed at banning most, and perhaps all, bromine-containing epoxies. Most EMCs still contain halogen, bromine compounds in particular, that are destined to be regulated into extinction just like lead in solder. Replacement of bromine with dubious choices like phosphorus, as a flame retardant, will only add more uncertainties, since phosphorus,—an element found in several *nerve gases*—will be in trouble sooner or later. A flame retardant *additive* is typically performance *subtractive*. But what if there were suitable high-temperature packaging plastics that were intrinsically flame retardant? Fortunately, there are many. One focus will be to identify such polymers with intrinsic low flammability, especially if they have other superior properties that are important for packaging.

A *perfect storm of change* has drifted across the packaging landscape that can help propel newer and better materials into the mainstream. We will compare metal, ceramic, thermoset, and thermoplastic materials for packaging to determine where each plays the best role. Thermoplastics are cheaper, environmentally acceptable, and boast near-hermetic properties superior to nonhermetic epoxies, but their performance is not as good as metals and ceramics. Thermoplastic properties are controlled and verified by the resin manufacturer who carries out the polymerization reactions. Thermosets can vary from run to run and the end user influences the final properties by carrying out *in situ* polymerization. The packager becomes the *chemist* (willing or not) and changes in the bake cycle alter cured properties like *glass transition* (Tg). More recently, bad EMC was not discovered until it was used to make millions of packages, making the final cost substantial. This situation cannot really occur with thermosets since final properties are checked and known before material is shipped. We will determine how well thermoplastics can meet a critical need for lower cost cavity packages for some, but not all mechanical devices. MEMS, MOEMS, as well as some *radio frequency* (RF) and optoelectronic devices, have created a growing market for low-cost cavity free-space enclosures that can be satisfied with new materials including thermoplastics, and fresh designs. Perhaps we will see a quiet packaging

revolution[3] that is initiated by universities, government laboratories, and small companies. But where polymer is inadequate, we will determine the best choice among the hermetic packages made with metal, ceramic, and glass. Next, we'll look closely at general packaging requirements, traditional solutions, and then move to newer strategies.

1.3 Multiple Functions

The package must perform several basic functions, such as connecting the device to the circuit board while protecting it, as well as many others that are discussed in the next section. We'll examine enclosure materials since this area can determine the level of protection, the package class, the package style, and the processes available.

1.3.1 Protection

The protection mechanism, materials, and reliability determine the basic package type. The early packages were fully hermetic, vacuum-sealed enclosures since low gas pressure was essential to operation of the electronic and optoelectronic systems. *Cathode ray tubes* (CRT) and the wide assortment of vacuum rectifier and amplifier tubes used hot filaments that would burn up in oxygen. But these devices used streams of electrons that would be impeded by the large population of gas molecules found in air at atmospheric pressure. The entire package was designed around the goal of maintaining a good vacuum. But solid-state electronics completely changed this and the vacuum package was no longer essential for mainstream electronics. Advancement in semiconductor chip-passivation allowed nonhermetic plastic to be used and this is still the most common form of package protection today. However, many devices and systems appear to need a higher degree of protection than nonhermetic epoxies can offer, or at least that is the common perception. Until recently, the choices were fully hermetic or nonhermetic—an all-or-nothing scenario. Figure 1.4 shows some of the first hermetic packages including a CRT.

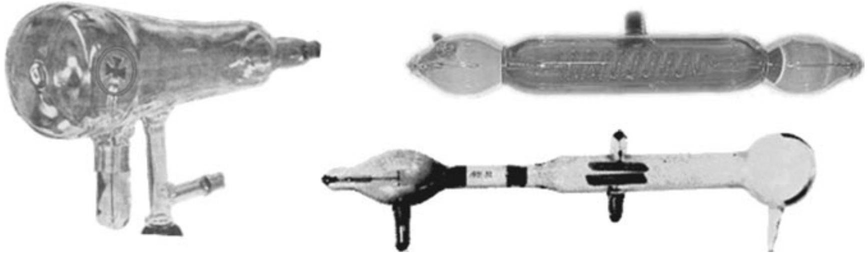


Figure 1.4 Early hermetic packages (late 1800s). (*Source: http://physics.kenyon.edu/EarlyApparatus/index.html*)

While the various free-space electron-emitter devices could only operate efficiently at low pressure, that is not the case for solid-state semiconductors, with few exceptions. We therefore need to examine the need for hermeticity when solid-state devices are involved. This includes MEMS devices that can be viewed as a solid-state type device with special mechanical features. The concern really comes down to *chemistry within the package*. Chemical reactions will cause changes that are usually undesirable. Some metals will oxidize and corrode. Solid-state devices can undergo change in the presence of air gases, especially oxygen and water vapor. In fact, water is the most significant molecule in terms of potential damage to devices and the package. Water can create two different problems. First, it is a medium for ions and a catalyst for many reactions, especially metal corrosion. This is why aircraft are stored in dry desert locations. Also, when a package adsorbs water vapor, it can become a "bomb" ready to literally explode under high-temperature conditions like those found in soldering. The adsorbed water instantly turns to steam that can crack the encapsulant or cause delamination that is appropriately referred to as "popcorning." Since water can cause more problems than any other environmental constituent, it makes sense to measure and define hermeticity on the basis of water for systems that do not actually require a vacuum. Water can also cause special problems for MEMS and optical systems and this will be covered later. On the other hand, MEMS fluid devices such as ink-jet chips use water-based materials as part of their operating materials.

1.3.2 Connectivity

The package absolutely must provide connectivity. The electronic package provides electrical connections but thermal links may also be required. A MEMS always requires electrical connections but several other types may be essential that pose completely new engineering challenges.

Electrical. The package provides the first-level (device to package) interconnect structure and must enable second-level (package to circuit board) electrical connections. Electronic devices require power, ground, and signal transmission paths. Power and ground connections are less critical and are often redundant in packages that have a high I/O count. In recent years, signal transmission has become an issue, as frequency—a function of the timing clock cycle—has moved into the higher Gigahertz realm. Package style is often dictated by the I/O range. A very high connection count, above 1,000 connections, typically requires a *flip chip in package* (FCIP) design since the common wire-bonding connection method either can't handle such a high level, the signal is degraded by the wires, or the one-at-a-time sequential nature of that method adds an

excessive cost penalty. MEMS devices are typically low lead count and so the interconnect is not usually an issue from the "pin count" and wire routing perspectives. However, since metal conductors must protrude through the package, they can have an influence on cost of hermeticity. Metal packages require insulating or nonconductive seals that are almost always hermetic. The insulators must be made of materials that are thermomechanically compatible with the enclosure and will bond to the metal. Glass and ceramic eyelets are used for metal packages and this requires high-temperature processing, all of which adds cost. Regardless of the package housing and wiring scheme, electrical connectivity is the most important first consideration.

Material transport. Electronic devices do not require any I/O beyond pathways for electrons, with few exceptions. MEMS devices can have substantial nonelectrical interconnect needs. While electrical connections are always required, gases, liquids, and even solids are requirements for some MEMS devices. MEMS gas analyzers already exist as do a variety of fluid pumps and controllers. A well-designed package should accommodate these needs. But some manner of quick connect/disconnect coupling is desirable even though manual connections for microplumbing appears to be the norm today as seen in laboratory-level prototypes. One can even envision future devices that will deal with nanopowders that could conceivably be pumped. We must consider ways of dealing with material transport and interconnects. Materials interconnect technology will be essential for future MEMS-based products. Fluidic MEMS is a significant emerging area with at least 50 companies and research organizations already involved.

Radiant energy. Some electronic chips, such the programmable UV erasable class, use packages that allow the entry of radiation, but this is not a common design. However, optoelectronic devices all require that their packages allow light either to enter, to exit, or both. Such devices include emitters, like *light emitting diodes* (LEDs), lasers, and various photodetectors including more sophisticated imaging devices, like *charge-coupled devices* (CCDs). Optoelectronics communications systems, especially those employed within the Internet, typically use optical fiber connections into and out of a metal hermetic package and are probably today's most expensive packages. Some cost several hundreds of dollars, but they provide extreme reliability and lifetimes can exceed 20 and even 30 years. The packages for imaging devices have some of the same attributes that are required for MOEMS and may serve as an initiation point for our analysis. Some of the display packages, especially those for moisture-sensitive systems like *organic light emitting diodes* (OLEDs), may also be useful for application to a MEMS and these avenues will

be investigated later. Most MOEMS devices will require a window that can be glass or plastic. Mating glass to package housings made of metal, ceramic, or plastic requires a more careful selection of materials and processes. But there are solutions for all cases.

External force. Pressure sensors and other force detecting and measuring devices need a mechanism for communicating with the external forces to be measured. The force can be one that surrounds the package, such as the atmosphere, or one that is contained within a closed system such as an automotive air-conditioning unit. The MEMS pressure sensor must be able to access the pressurized gas or fluid, or whatever material or device is exerting the force. But it is nevertheless necessary to exclude undesirable materials. Fortunately, it is possible to design a package that can block the entry of external contamination while still linking the force to the MEMS sensor by using a membrane or some other deformable material with barrier properties. MEMS pressure sensors are one of the most important products today and several companies have solved this packaging problem even for extreme conditions of the engine compartment. Motorola, a longtime manufacturer of automotive sensors including MEMS, has explored several approaches to sealing out the environment while allowing external forces to be conveyed to the MEMS chip. The most commonly used sensing mechanisms rely on either the piezoresistive effect or an electrostatic variable capacitance mechanism. The piezoresistive pressure sensor relies on changes in electrical conductivity resulting when force deforms the sensor material. The capacitive pressure sensor uses a pressure-sensing diaphragm as one side of a capacitor pair; force or pressure reduces the gap producing a corresponding change in electrical capacitance that can be monitored.

The MEMS sensor can be coated with a highly elastomeric gel (low modulus; <0.1 GPa) that is hydrophobic and chemically resistant. The gel can be applied as an encapsulant over the chip and wire bonds. Additional mechanical protection such as rigid vented enclosure may be needed over the gel. Another concept is to surround the chip with hydrophobic fluid and seal the package with a thin, stainless steel diaphragm but this will add extra cost. The simplest approach, according to Motorola, is to use a barrier coating over the MEMS sensor.[4] The most common materials are silicone gels and conformal coatings. Silicone gels can be used to fill the package cavity and protect the silicon die and interconnect from corrosion. These gels can be dispensed as thick coatings (several mm) or used to completely fill the sensor package cavity. Suitable commercial gels are available mostly as silicones, but thin coatings like parylene, and thicker conformal coatings including UV curable, should also be considered.

1.3.3 Compatibility; chip-to-package

The first-level chip-to-package connection method will normally determine both the geometry and finish requirements of the package interconnect inside the package. The three common first-level interconnect methods are *wire bonding* (WB) (by far the most common), *tape automated bonding* (TAB), and *direct chip attach* (DCA) that is generally called flip chip. Since the active side of the chip is flipped down; the active side is up for wire bonding. FC requires that the package bonding pads exactly match the footprint of the chip bumps. The package interconnect surface finish must also be compatible with the FC assembly process that is typically solder reflow. However, conductive adhesive bonding and thermal compression processes are also used. Flip chip generally requires that underfill, an organic adhesive or encapsulant, be interposed between the bottom of the flip chip and the package "floor." This means that the package material must permit strong adhesive bonding to take place. While FC may seem the simplest method of connecting a chip to a package, there are subtle complexities, and the flux, underfill, chip passivation, and package pads and body must all be compatible. When all things are considered, flip chip is not the first choice for MEMS, especially since the underfill can add significant mechanical stress. However, there are some features of flip chip, like the gap between chip surface and substrate, that could be of value. The gap can serve as free space needed for MEMS mechanical action.

Wire bonding is the most versatile first-level interconnect method since it allows for "programmed" routing. The wire bonder connects one end of a thin gold wire to a chip pad and the opposite end to the first-level package pad. Aluminum wire is used to a lesser extent and copper wire technology has been developed but not widely adopted. Wire bonding will accommodate modest changes in chip pad size and pad layout without having to redesign the package. This programming and routing ability is a very important feature since chip mechanical dimensions can change several times through the lifetime of a particular device. However, this common "die shrink" strategy used in conventional electronic devices to gain electronic speed and to reduce cost may not become common in MEMS, at least at this relatively early stage in the industry. Nevertheless, wire bonding offers many advantages for MEMS and it is likely to remain the most popular first-level method. Figure 1.5 shows a wire-bonded chip.

TAB bonding can be viewed as a special form of wire bonding where the first-level connection "wires" are an integral part of the package. Flexible circuitry-type products are typically used for such packages since the TAB *inner lead bonding* (ILB) structure can be readily fabricated from these thin materials. The author views TAB as a specialized flexible circuit. Polyimide (PI), because of excellent high-temperature performance, is the polymer class of choice for dielectrics, but the newer

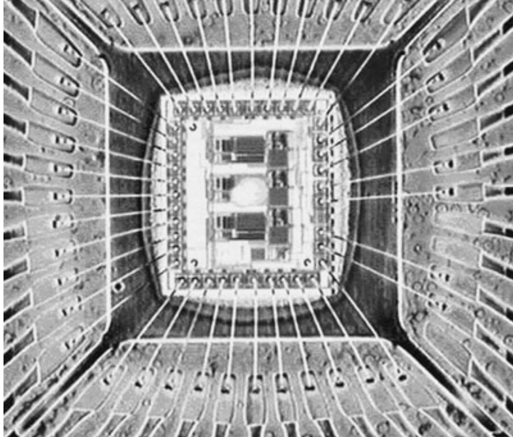


Figure 1.5 Wire-bonded chip.

liquid crystal polymer (LCP) class of thermoplastics is gaining share since moisture absorption is much lower. A "window," or access opening, is formed in the dielectric substrate or base film, to permit bare metal conductor leads to extend over the open space in cantilevered fashion. These thin metal *flying leads* must be fabricated with precision so that the ends can be aligned to the chip pads for bonding. Unlike wire bonding where the bonder positions each wire, TAB requires that the entire "wire array" be aligned by positing the structure over the chip pads. Some bonding techniques form all the bonds at once (gang bonding) while others make bonds one at a time to allow shaping and steering of the lead, resulting in higher precision. The interconnect structure must also have a metallurgical finish that is compatible with TAB thermocompression bonding. Gold is the metal of choice and it can be applied to the TAB "fingers," the chip pads, or both.

The metal leads for conventional TAB fan out and away (called fan-out style) from the chip to create a larger footprint that enables easier bonding to the printed circuit board that typically uses lower-density patterning processes than TAB. These outer leads can be bonded to a PCB by hot bar soldering to complete the second-level connection that is called *outer lead bonding* (OLB) in the jargon of TAB. Figure 1.6 shows a conventional TAB package; also called a *tape carrier package* (TCP). TAB is one of the earliest flex-based packages, a concept that was introduced in mid-1960. This type of package is especially suitable for MEMS ink-jet chips and this topic will be covered later. There are two distinct variations of the TAB package. The first-level interconnect is well established and is considered an excellent system, but the second-level scheme leaves much to be desired since hot bar solder bonding is not really a good assembly process;

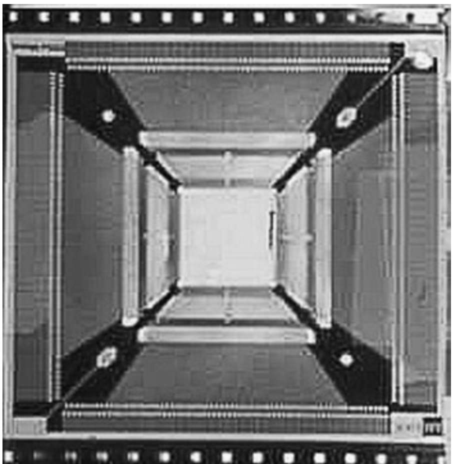


Figure 1.6 Tape automated bonding.

it requires special equipment, assembly is slow, and yield can be poor due to shorting and lead breakage. One design solution widely used for MEMS ink-jet chips is to incorporate the flying leads into a flex circuit to completely do away with the outer leads. This design can be called TAB-featured flex, a term coined by the author in the 1980s. A second approach is to convert the outer lead structure to bumps on the bottom of the package. IBM's *tape ball grid array* (TBGA) fans the leads outward while Tessera's micro-BGA (μ-BGA) fans the leads inward to produce a *chip scale package* (CSP). The great value of bumping the outer lead termination is that the package becomes an SMT type that can be assembled to printed circuit boards (PCBs) using a standard solder reflow assembly line. Both BGA package designs utilize area array bumps, making them high-density systems. While credit goes to Tessera for inventing the fanned-in package μBGA, IBM appears to be the first to use TAB inner leads and bumps to replace outer leads. Both designs provide special attributes and both are commercially available and quite successful.

1.3.4 Compatibility; package-to-printed circuits

Most packages are joined to PCBs by soldering and this adds several requirements. First, the package must have the correct lead geometry and metallurgical finish for soldering. The connection sites must be fabricated with enough precision so that the package pads can be aligned with circuit board pads by automatic pick-and-place machines. The package interconnect system should be robust enough so that it is not

damaged in normal handling. In the past, high I/O perimeter-type packages had been made with such thin metal leads that inadvertent bending caused misalignment resulting in "opens" and "shorts." Area array packages can be made to be very sturdy and durable, but other compatibility problems such as warp can crop up. A BGA can have low-assembly yield if the package base is so warped that some solder bumps cannot make contact with the PCB.

The package interconnect metallurgy must be compatible with the circuit board finish and the assembly-joining materials. But environmental initiatives like RoHS, have placed us in the midst of change for metal finishes, solders, and fluxes. There is no full consensus on choices, nor is there likely to be agreement on a single system. Different companies and countries will probably use different lead-free alloys and finishes. New rules restricting the use of not just lead, but other materials, are changing most of the electronics industry, especially PCBs and packages. Any new package should be designed for lead-free assembly since that is rapidly becoming the norm. The next, and perhaps the most important criterion from a materials perspective, is that the package must withstand the assembly process. Lead-free alloys are typically processed at about 40°C higher than the traditional tin-lead eutectic alloy, and that requires package materials and constructions that can survive up to 260 or even 280°C. Poorer wetting of some of the lead-free alloys has prompted assemblers to run even higher reflow temperatures. Fully hermetic package materials can usually survive this temperature extreme that has a duration of only 5 to about 20 s, but plastic materials need to be examined more closely. Nonhermetic epoxies, for example, can be marginal. Even if the epoxy does not degrade to an unacceptable level, some outgassing occurs that can cause problems with mechanical and optical devices. However, several thermoplastics are commercially available that can withstand about 300°C without melting or decomposition. Thermoplastics also tend to have low outgassing characteristics and are therefore candidates for consideration in the MEMS packaging area. But such extreme temperatures can damage devices and some MEMS devices and several optoelectronic components may require lower temperature assembly. One alternative is conductive adhesive assembly that requires no more than 150°C for hardening. Some can even be processed at 100°C. Since thermoset adhesives cannot melt after curing, they are not reworkable, but they will not melt during solder reflow and can be used for FC assembly within a package.

1.3.5 Routing

Package routing for electronic chips only involves paths for electrons. MEMS may also need electronic routing. But since MEMS can also deal with materials, the package may also need to route gases, liquids, and

perhaps even solids. MOEMS may need routing for electromagnetic radiation, including visible light and infrared for signals. MEMS and MOEMS have brought new meaning to package routing.

1.3.6 Electronic routing

Some devices do not require that the first-level connection pattern, or footprint, be any different from the second-level connection pattern to the circuit board. The interconnect structure therefore has no geometric translation or routing. But the most common chip-to-package interconnection process, namely wire bonding, provides a modest level of intrinsic routing. The package first-level bonding pads must have a larger footprint so that they are not covered by the chip. The wire bond thus extends a connection outwardly from the chip pad to package pad. The total structure can be viewed as the interconnect and routing system. Wire bonding can also route in the third dimension. A die stacked on top of another, can be wire bonded even though it is at a different height. Die stacking can be a useful concept for MEMS, especially when mechanics and electronics are not integrated into a single chip.

While the simplest package can have bond in-package pads and exterior bond sites that have the same physically dimensioned layout, many have a routing scheme that allows the layouts to be different. Package routing therefore involves a conductor wiring system that translates the chip pad geometry to a different package assembly footprint. Two common routing architectures, as discussed under TAB, are fan-out, where the second-level pattern becomes larger than the first level, and fan-in, where the assembly pad footprint can be similar or even smaller than the chip pad layout. The fan-in packages are often about the same dimensions as the chip, and these products are called CSPs if they meet a certain chip/package size ratio. Routing can be in the form of thin metal conductors that are made by printed circuit techniques and this is the method for most area array packages typified by the BGA. Even TAB-like packages such as the µBGA and the TBGA mentioned earlier, have routing structures created by circuit processes. MEMS devices presently tend to have low lead counts and simple pad layouts that do not always require routing built into the package. Many accelerometers require only four connections. Wire-bonding routing, or none at all, appears to satisfy present needs.

1.3.7 Materials routing

Some MEMS chips (in the biological and chemical areas) transport, control, and route fluids or gases. But as MEMS grows more complex and sophisticated, there will be a need for packages that “route” materials. A MEMS chemical analyzer will certainly need access to the sample to be analyzed. Various chemical reagents will also be needed. Packages that would

convey the sample and reagents as well as electricity and signals to and from the primary MEMS chip are likely to be needed. One can envision a pluggable interface for materials where sample after sample are introduced to the MEMS analyzer chip just the way samples are presented to analyzers in the macro world. Future MEMS-enabled products could have the equivalent of the *central processor unit* (CPU) and support chips as seen in computers. But a better model may be laboratory analyzers where the various subsystems are replaced by MEMS chips.

Light will also be conveyed to desired locations and from different sources; this will be needed for some spectrophotometers that cover a wide portion of the spectrum. The MEMS total system package could enclose a complete miniaturized "macro-performance-analyzer." Macroscale units are often self-contained units with plumbing, pumps, valves, and mechanical mechanisms to move samples and reagents around the system. While a complex analyzer could become a MEMS *system-on-chip* (SoC), it is more likely that a *system-in-package* (SiP) will be built that mimics that behavior of today's equipment that is many magnitudes larger and heavier. But it is also likely that package modules will be connected to "motherboards" that route power, signals, and materials.

1.3.8 Mechanical stress control

Mechanical stress on a chip is always a concern, but the issue is much more important for MEMS. The package base ideally would have the same thermomechanical properties as the chip, but this is not always realistic when lower-cost polymer-based packaging is the best choice. In fact, many ceramics do not match the *coefficient of thermal expansion* (CTE) of silicon but come much closer than organic dielectrics. But if a package were made with the same low-expansion properties as chip materials, there would be a thermomechanical mismatch with the printed circuit board that typically matches the CTE of copper that is around 17 to 18 ppm/^{o}C. The PCB dielectric is matched to its copper conductors to make the structure less prone to curling and warping during temperature cycling and this is especially important for thin materials like flex.

Some packages (especially those based on flexible circuitry) like the μBGA have built-in interconnect compliancy. Wire bonding also mechanically isolates connections through the wire. A common solution however, is to interpose a somewhat elastomeric material between the chip and the package. Organic die attach adhesives can be designed to withstand much of the stress of differential thermomechanical expansion and are sometimes referred to as low modulus or compliant adhesives. The most common form is paste, but films are also available. The die attach material choice is more critical for MEMS because of higher stress sensitivity. Flip chips use an entirely different mechanism for controlling stress. Underfill—a laminating adhesive that is also an encapsulant—locks the

bumped chip to the substrate to greatly reduce differential movement. The high-modulus chip constrains movement of the lower modulus substrate. But we need to note that the objective of underfill is to reduce stress on the interconnect (bump) structure, not the chip. In fact, since the chip is used to restrain movement of the substrate, mechanical forces on the chip can be high. Stress-reduction techniques like wafer thinning may not be suitable for 3D MEMS devices. The FC is probably not the first choice for MEMS devices that are sensitive to mechanical stress, at least with the standard underfill method. However, systems with no underfill, or selective underfill could have merit.

1.3.9 Thermal management

Since all ICs and MEMS chips are powered by energy, heat is a waste product that must be removed if excessive. Thermal management features can be designed into the package when necessary. Heat is removed from a chip from the active side and also the back side. In the case of flip chip where the active side is down, the bumps serve as a thermal path to the package, but underfill can also be designed to be more thermally conductive. In both cases, heat is conducted to the bottom of the package and it can be transferred to the printed circuit board through the package second-level conductors. In some cases, a thermal pad of heat block is designed into the bottom of the package. For maximum effectiveness, the package thermal structure must be bonded to a metal pad on the circuit board that is designed to convey heat. A solder joint is usually formed between heat block and the circuit board. A heat sink can also be designed into the package to remove heat from the back of the die and from the top in the case of FCIP. The die attach adhesive can also be filled with thermally conductive materials, also electrically conductive and insulating, and these are the most common products. Most MEMS devices do not require thermal dissipative packages. MEMS actuators are efficient and there is little by-product heat. But chemical reactors, especially power engines like rockets and turbines, will generate considerable heat. MOEMS devices used in high-intensity digital projectors are subjected to source heat that must be considered in the package design.

1.3.10 Assembly simplification

A good package is designed to enable the simplest and most easily automated assembly process. Today's de facto standard assembly process is surface mount and any new package designs should attempt to fit this method although there will be exceptions. However, many fully hermetic packages, especially those made of metal, have leads that protrude from the sides and must be hand assembled. Hand assembly is no longer acceptable for high-volume products and any MEMS product intended for

reasonable volumes should utilize an SMT package. But this may become impractical for MEMS devices that require material I/O such as pumps, at least using today's packaging concepts; for example, there will be a need for plug/unplug sample and reagent container packages. Later, we will investigate novel packaging ideas that could allow "remarkable" connections that may start off as manual, but could be automated just as seen in the macro world.

1.3.11 Performance enhancement

Some packages can improve the total performance of a device although others may cause reduction but with compensate cost savings. An FCIP design using lower-cost organic substrate would normally have poor reliability. The first-level connection would typically fail after a few hundred, or maybe even a few dozen thermal cycles, as the differential expansion of chip and package caused joint fatigue. However, the addition of underfill provides at least a tenfold boost to reliability performance. The package can also boost electrical performance by reducing "parasitics" and this can require an insulator with a specific dielectric constant or the addition of embedded passive devices. MEMS devices will have even more functions that can be enhanced by the package such as acoustics for a MEMS microphone.

1.3.12 Testability and burn-in

While chips can be tested at wafer level, the challenge of *known good die* (KGD) before packaging remains a problem and MEMS substantially increases the level of difficulty. A package should enable testing and even "burn-in," depending on the device and application. MEMS presents a much greater challenge since mechanical, or some other nonelectrical input can be required to test the chip. Electrical tests can only go so far. Mechanical interaction is probably required for high-assurance testing. Even if wafer-level testing is used, the MEMS chip performance parameters can change after packaging, making it imperative that the package enable adequate testing. But package assembly to the PCB can also alter performance of many inertial sensors. There may be no easy answers or single test strategies.

1.3.13 Removability and reworkability

A package is commonly defined as a system that can be assembled to a circuit board or subsystem and then removed if necessary. When a chip is bonded directly to a circuit board in a way that prevents its easy removal without damage to the board, most would not include this arrangement as a true package. *Chip-on-board* (COB) and most FC assemblies fall into

this nonpackage classification. However, if the FC does not use underfill or the underfill is readily reworkable, then it may qualify as a package provided that the nonunderfilled assembly was reliable without having to be placed into an enclosure. But some would go a step further and require that the package be able to be removed and re-assembled, or at least repaired in place, by reflowing the solder joints or adding more solder by manual touch up.

1.3.14 Standardization

Since circuit board designs use *computer-aided design* (CAD) software with a parts library and nearly all assembly is automated, it is important to have packages that fit a standard footprint and meet certain physical requirements. Packaging standards have become well established in terms of physical dimensions and connector layout. Progress continues with agreement on performance test methods, specifications, and standards. However, MEMS, with so many special requirements, adds a new challenge to standardization. This issue is exacerbated since MEMS devices need their own set of packages that can accommodate the new requirements introduced by the mechanical (and optical for MOEMS) features. Cost can only be reduced to a minimum when standards that can serve as a guide to material suppliers, board makers, and equipment suppliers, are in place.

1.4 Package Types

There are many ways of classifying packages and they include type of chip connection, interconnect geometry, body materials, number of chips, type of chip, and level of hermeticity. We will consider hermeticity level as one of the most important criteria since this will effectively divide packages into three types: one that meets requirements for MEMS, another that is being developed especially for MEMS, and the common overmolded plastic package that is not well-suited for MEMS. But we should be aware that hermeticity will have no validity for some MEMS devices, especially fluidic types that will probably use water and aqueous solutions internally. However, we may want to consider selective hermeticity, or moisture tolerance. Ink-jet chips can and must tolerate water internally, but the electrical interconnect still requires protection. The solution here is selective encapsulation.

1.4.1 Fully hermetic packages

The fully hermetic package was first developed over a century ago and has served both the electronics and optoelectronics industries quite well. The CRT that was first demonstrated in the late 1800s used a sealed

glass vacuum enclosure. The Braun tube, for example, was a scanning CRT display system that used a glass envelope to seal out the atmosphere and maintain the required vacuum. Metal wires entered the envelope and were sealed by the glass, making gastight connections. The package made up most of the CRT contributing most of the cost and this is still true today. Later, electronic vacuum tubes were developed, starting with the Fleming diode that also used a glass envelope. A few years later, De Forest introduced the *breakthrough* triode (Audion) that was able to amplify, making it the *first active electronic device*. DeForest also recognized, contrary to the view of colleagues, that a very high vacuum improved lifespan and performance. Figure 1.7 shows a DeForest tube. Many of the early opto and electronic devices required a vacuum to operate because the flow of electrons through free space was part of the operating mechanism. Thus, the goal of a package with a "perfect" vacuum was set very early and it is no wonder that many in the device and packaging field, judge packaging merit on the basis of sealing out the entire atmosphere. However, this persisting view is much too general, as we will see later.

Today, only a small minority of products require a true vacuum. Some of these are MEMS devices with mechanical action that air molecules can impede, but most devices can operate in the presence of gases, and some MEMS analyzers require the introduction of gas. Yet the century-old tradition of routinely specifying a fully hermetic sealed enclosure continues for many products that could probably operate in the presence of gas molecules. While the package has changed from glass to other materials, the idea of making a near-perfect gastight enclosure has remained too constant. A policy of specifying a package enclosure that is essentially free of any environmental materials might be satisfactory if not for the high cost

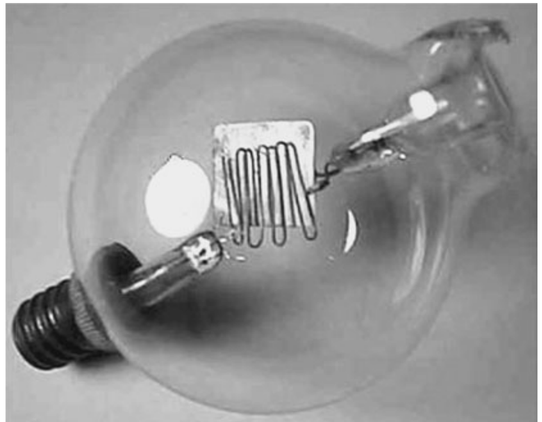


Figure 1.7 DeForest tube. (*Source: Website of American Museum of Radio and Electricity, Bellingham, WA.*)

penalty and a few other detractors. There is no value in a policy of using an absolutely safe and century-proven package that will bankrupt the business. The metal or ceramic fully hermetic package may be required for applications that cannot use the nonhermetic plastic package, but an intermediate package could change this. The biggest issue is cost, and the hermetic package often ends up being much more expensive than the contents, perhaps 70 to 85 percent of the total product. Compare this to only 3 to 5 percent cost for standard nonhermetic packages used for low-cost electronics. Some packages cost less than a nickel, including materials and assembly, but not the chip. The cost issue has been a *killer* for some of the clever new devices including MEMS, but solutions can be developed and this will be our goal. The package enclosure material can provide the means of limiting chemical reactions inside the package and this is a better way to investigate criteria. We need to think in terms of preventing unwanted in-package reactions, especially corrosion. Only a few atmospheric constituents, like water, are important, making hygroscopic properties more significant. Figure 1.8 shows a metal hermetic package.

Glass. Glass, as mentioned earlier, was the very first electronic and optical package material. Glass provides a good gas and moisture barrier, although not a perfect one. Glass is also somewhat easy to shape as demonstrated by light bulb manufacturing that is highly automated. However, light bulbs require only two, or four, connections for fluorescent bulbs, and their high volume and few number of designs make full automation practical. Glass vacuum tube manufacturing has also been automated, but again note that the number of interconnects, or I/Os, has been small, and the socket interface has also made automation easier. Glass is not an ideal choice for packaging solid-state devices that require high lead count. However, optoelectronic devices often require a window, and glass is totally

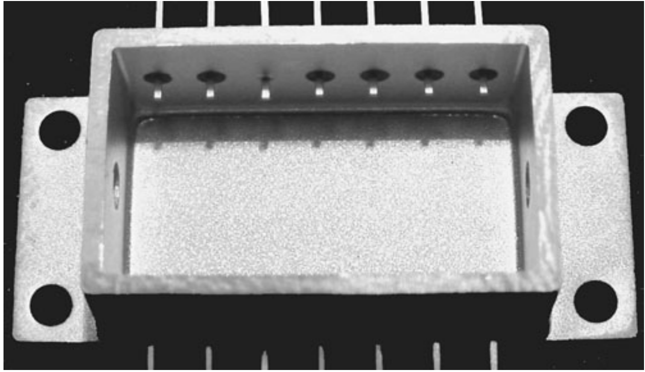


Figure 1.8 Metal hermetic package.

suitable here, but the package body can be plastic, ceramic, or metal. Several MOEMS devices, including the DLP mirror chip from Texas Instruments, use packages with bonded glass windows. We will see later that glass can easily be bonded to other packaging materials by automated methods.

Ceramic. Ceramic has become a preferred material for lower to modest cost packaging, including hermetic types. While not as low cost as plastics, ceramic is generally more economical than glass and metal, especially because the ceramic circuit processes, once called ceramic hybrid, can produce chip carriers at a modest cost.

Metal. Metal packages are the "gold standard" in both performance and cost. Material cost is not always the primary factor since metals are often cheaper than the plastics used to produce very low-cost packages. The process typically is the dominating factor for total packaging cost, and metal shaping and finishing processes for packages can be expensive. Machine shop-type methods like milling and drilling are labor-intensive, slow, and wasteful. The need for insulation for pass-through connectors also adds cost; ceramic or glass isolators are commonly used and require positioning and lengthy high-temperature firing. The resulting metal package is gastight and easily passes the helium fine-leak test. *Residual gas analysis* (RGA) also shows that atmospheric gases do not enter. Reliability ratings can often be extrapolated to 100 years or more. But metal packages can show an increase in gas content due to outgassing, unless extreme measures are taken to eliminate trapped gases before the package is sealed. Hydrogen, for example, is often emitted over time since it can be trapped in the metal during electroplating. Gold is usually plated over the entire package, both inside and out, after fabrication is completed. This operation can cause hydrogen to be adsorbed into the base metal and into the gold where it is released over time but the release rate is accelerated by heating. Hydrogen getters are often added to metal packages that contain devices such as GaAs, that are sensitive to this gas. Package materials other than metal must be considered for MEMS to cut cost and gas evolution, especially for devices that are used as sensors or contain palladium or platinum since these metals react with hydrogen to produce by-products that can harm some semiconductors.

Combinations. Materials can and should be combined to produce packages that are better suited to applications and are more cost-effective. All packages use more than one class of material but are categorized by the main constituent or by the enclosure or platform composition. Metal enclosures can have ceramic chip carriers that contain one or more chips or even other devices such as optical types. But the end result, while

more versatile, is still expensive, and should not be the first choice for MEMS. Metal is also being combined with plastics but the result is usually a nonhermetic package at a very affordable price. Metal inserts and lead frames are commonly molded into plastic enclosures to produce low-cost nonhermetic packages. However, packages with plastic bodies and metal lead frames are generally just referred to as plastic packages since it must be assumed that metal will be used to carry electrical current into the nonconductive plastic enclosure. Ceramic and plastic may also be combined but the plastic is usually in the form of an underfill, for FCIP, or encapsulant fill. Most refer to these as ceramic packages since the main body is ceramic. The ceramic packages also contain metal conductors that may be in the form of metal-containing cermet (ceramic or metallic) ink. While conductors may be referred to as ceramic inks, the cermets are mostly metal and only the metal contributes to the electrical conductivity.

1.4.2 Nonhermetic plastic

The nonhermetic plastic package, also called *plastic encapsulated microelectronics* (PEM) especially in military circles, became mainstream products with the DIP that is still used today. The DIP that helped make packaging a high-volume low-cost commodity was shown earlier in Fig. 1.2. Electronics perhaps owes as much to the development of the plastic package as it owes to the IC. A die (chip) is typically attached to an MLF using die attach adhesive. The first-level connection is made by wire bonding the chip's pads to pads on the MLF. The entire structure is then overmolded with epoxy molding compound using the transfer molding process. Mold compound, a solid blend of epoxy resin, hardener, filler, and additives, is heated to the melting point, forced into a mold that contains the lead frame assembly with the bonded chip, and heated to polymerize the material. The mold compound comes in direct contact with the chip, wire bonds, and MLF.

Surface mount packages are made by the same basic process as the DIP but the MLF has a different geometry to provide the SMT configuration. A BGA design can also be made with plastic and is referred to as a PBGA. Here, organic substrate generally replaces the MLF. The PBGA has a higher cost than MLF products but offers much higher density and other features. The DIP, SMD, and PBGA all use essentially the same processes with very similar epoxy encapsulants even though they span 50 years of development. A few MEMS devices can be packaged by overmolding but special processes must be used to prevent encapsulants from contacting the mechanical parts of the die. But there is a phenomenon that occurs with overmolding, even if the mechanical parts of a MEMS chip can be protected. The EMC shrinks during curing and creates stress on any chip, which can reduce performance.

Perimeter style. Many packages use an interconnect structure where conductors only protrude from the perimeter of the package. This package style, while limited in the total number of I/Os, can often be produced at lower cost than area array styles. MEMS does not typically require the high I/O count seen in electronic devices like CPUs, so perimeter style can be adequate in most cases. However, newer package fabrication methods, to be discussed later, can produce area-array-style cavity packages suitable for some MEMS devices, at a lower cost than older methods used for perimeter.

Area array. The area array package introduced in high volume in the 1990s was aimed at solving the problem of adding more I/Os to a shrinking package. In some cases, area array offers higher electrical signal performance and also improved cooling. Since MEMS is not considered a high I/O device, at least at this stage, area-array-style packages are an open option, though not a requirement.

Cavity formation. Cavity-style packages are designed to have inner space, or a chamber, that is also called free space. Some refer to them as air cavity packages but this definition may prove to be narrow as the cavity can be filled with a different gas or even a solid. Cavities can be formed by machining metal, by forming metal with a press, or even by molding metal powders. However, the metal mechanical machining approach has been widely adopted for metal hermetic packages. The cavity is sealed after the device has been attached by adding a lid. The lid can be welded or soldered to complete the metal cavity package. Ceramic cavity packages can be formed from green, or unfired, ceramic materials. The package can be completed by sealing a ceramic or metal or even a glass lid. Some MOEMS devices, like the DLP, use ceramic cavity packages with a soldered glass lid for hermeticity, but this requires metallizing the edge of the glass and ceramic.

It is more difficult to form a cavity package using the common transfer molding method that is so widespread to make nonhermetic plastic packages. However, it is not impossible. This overmolding process injects melted thermoset epoxy resin and hardener against a bonded chip and package platform held in a mold. The chip carrier can be an area array substrate or a perimeter lead frame. Since the mold cavity is filled with the liquid resin mix, there is no mechanism for producing a cavity.

But there is another plastic molding process that is ideal for 3D shapes and cavity formation and it will be mentioned briefly and covered in more detail in the *near-hermetic package* (NHP) section. Thermoplastic injection molding is one of the most common plastic part shaping processes in use; blow molding is also common, but more applicable to bottles and similar containers. Billions of plastic parts are made by injection holding. The parts process involves melting thermoplastic resin, injecting into a closed

mold letting the resin cool to a solid in a matter of seconds, opening the mold and ejecting the finished part. The cycle is automatically repeated and can be run almost indefinitely. The mold can be designed to produce a boxlike cavity or nearly any shape desired. Since high-temperature thermoplastics are considerably better than epoxies as moisture and oxygen barriers, I have referred to this type of cavity package as near-hermetic although others have called this the in-between class—quasi-hermetic. Figure 1.9 shows thermoplastic injection-molded packages from several sources.

1.4.3 Overmolding capped devices

Electronic and mechanical devices can be capped, or sealed, at wafer level, to prevent contamination and entry of encapsulants. Usually, a tiny silicon or ceramic cap array is placed over the active mechanical area of the chip and then it is sealed or bonded. The size of the cap must be small enough so that chip bonding pads are left available for first-level connection, usually by wire bonding. Once capped, the device can be overmolded like any ordinary electronic chip. Note that considerable development is underway in the MEMS capping area but there is considerable *intellectual property* (IP) already in place starting with patents filed in the late 1980s. After die attach and wire bonding on a carrier or lead frame, the package can be overmolded but we should be aware that the hot epoxy shrinks during polymerization and contracts on cooling. This adds mechanical stress that will degrade the performance of some MEMS devices such as accelerometers and gyroscopes. A cavity package can avoid such stress although the die attach adhesive can be a stress factor that should be chosen carefully. Note that some accelerometers and most, if not all gyroscopes, cannot be overmolded even when capped.

Wafer-level; 0-level. Since nearly all solid-state and MEMS devices are produced in wafer form, the scheme of adding or creating the package using a wafer is a very appealing one. WLP has been gaining attention since 2000 and several products are now commercial with many more on

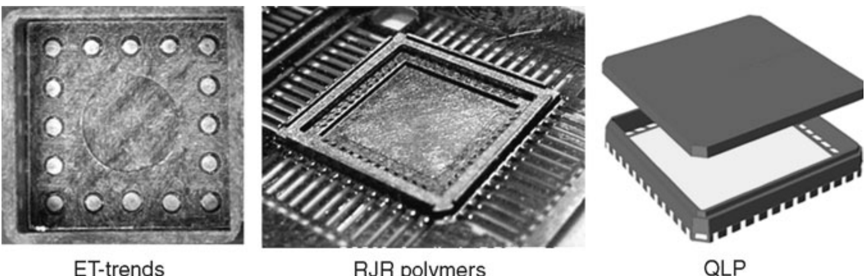


Figure 1.9 Injection-molded cavity packages.

the way. While WLP for electronic devices is mostly aimed at reducing cost, MEMS receives special benefits such as protection of mechanical functions. Wafer-level capping will be covered later, but it may suffice to say that MEMS chips can be protected and even made fully hermetic using WLP methods. Some refer to wafer-level capping as a 0-level process since it occurs before first-level chip connection. Although capping only affords protection at this time, we will explore WLP concepts that can also provide electrical interconnects in later chapters.

1.4.4 Near-hermetic package—a new class

There have only been two major package classes available and each is at the extreme of the "humidity spectrum." The fully hermetic package serves very high reliability and specialty areas including military and telecommunications. The plastic nonhermetic package is at the opposite end of the scale and is most suitable for general electronics, but this requires that the chip be passivated or otherwise made suitable for nonhermetic enclosure. The nonhermetic class is not generally used for more demanding devices and was not suitable for MEMS until the development of hermetic wafer-level capping. There are other package designs, but most fall into the nonhermetic class such as the FCIP discussed earlier and used for most computer CPUs; the back of the die is exposed and the front is only protected by a few mm of nonhermetic underfill. But none of these are ideal for a MEMS, although the fully hermetic class is used for high-end MOEMS devices like the DLP from Texas Instruments.

Overmolding is generally unacceptable for all but a few capped MEMS devices such as low-end accelerometers, and even here, encapsulant in direct contact with the chip degrades performance. A MEMS-specific package that is affordable would fill an obvious need but a solution is still not available. Since hermeticity can be a critical parameter, the plan should be to develop packaging concepts that provided maximum, but not necessarily full hermeticity if the benefit is substantial cost reduction. The second key requirement is that the materials and processes enable low-cost, high-volume production. One might summarize the goal as "Good enough and cheap enough." This type of package can be referred to as NHP and will be covered in detail later in several chapters. Here is the background that led many of us to this way of thinking.

In the year 2000, Arizona State University (ASU) helped organize a MEMS packaging workshop with help from the National Science Foundation (NSF) which wanted input from industry and academia. Organizer Ampere Tseng, a professor at ASU, asked the group if it might be possible to invent a quasi-hermetic package for MEMS. Professor Tseng felt that MEMS technology was being held back by expensive fully hermetic packages made of metal or ceramic. The group concluded that funding would be needed to move MEMS packaging ahead since the devices

were doing quite well, thanks in part, to very generous U.S. government funding. MEMS was not yet a large enough market to induce much industrial research, at least from packaging foundries. This author wrote a white paper that was submitted on behalf of the group that made the arguments for funding for MEMS packaging.[4] Later, a small coalition of would-be problem solvers began using the term NHP in place of quasi-hermetic, but there is no official definition.[5,6] During the last few years, a few small groups of developers have sought to test out the NHP idea—a package that is "good enough" and "cheap enough," whatever that means. The NHP, while not well defined, is emerging more as a strategy for low-cost packaging that provides a sufficient barrier so that a device and interconnect meet the customer's actual performance expectations. The NHP challenge has led several companies to experiment with, and even commercialize thermoplastic packages that fall somewhere between fully and nonhermetic products. Since the goal is high volume at low cost, the golden rule here should be, "Everything should be made as simple as possible, but not simpler," one of Albert Einstein's (1879–1955) most brilliant statements.[7] While MEMS was the initial target, the new plastic package concept may have broader viability, especially if the total economics are right. Later, we will examine MEMS packaging requirements and determine how close the NHP idea comes to meeting them. But even if near-hermeticity, as achieved by the most suitable plastics, will not provide enough protection, the level might be improved with barrier coatings that could deliver full hermeticity. Several types of NHP are shown in Fig. 1.9.

Barrier coatings for plastics. There are several thin coatings that might be applied to plastic parts that could improve hermeticity, including molded cavities. Some are metal that would require selectivity, but several are inorganic dielectrics. Metals are already routinely applied to plastics, and processes such as plating are well established. Since metal is an excellent gas barrier, developers may want to investigate metallized plastics in an effort to produce low-cost hermetic packages. Plastic can be easily plated with metal without adding much cost, but if selective platings are required, this will add additional cost. The main problem would be to come up with a scheme to coat the package without shorting out the electrical interconnect structure. Some approaches will be presented later in the book. But glass and ceramic coatings have also been applied to plastics and these types of coatings would not cause shorting. These approaches will also be covered.

1.5 Reliability and Qualification

Reliability has been a concern for all electronic packages but requirements have been fairly well sorted out for electronic devices over its long history. But MEMS requirements are still evolving and the level of

hermeticity for each type of device is not well established. The approach of specifying a package that provides fully hermeticity, whether needed or not, is no longer acceptable and should be considered a flawed practice from the engineering and design point of view. The package needs to suit the device and application requirements, and to buy more at added cost is a disservice to the customer since the added cost brings no benefit. Considerable work on MEMS reliability has been done at Sandia National Laboratories, where a sophisticated failure analysis laboratory operates and data are reported on a regular basis.[8]

1.6 Summary

Packaging has a rich history that goes back more than a century. While all early packages were of the fully hermetic class, the nonhermetic plastic package for semiconductors was the first breakthrough for high-volume low-cost packaging. The plastic package, based on thermoset epoxy molding compounds and the transfer molding process, provides very low-cost automated packaging for most electronic devices but is unsuitable for MEMS without special prepackaging. The fully hermetic package, while technically suitable for MEMS and MOEMS, adds substantial cost and also produces packages that may not be compatible with automatic SMT assembly. The obvious conclusion is that a new class of packaging is needed that would fall between the other two extremes. The term NHP has been applied. MEMS not only requires, but deserves development of packaging designed specifically for this rapidly expanding area of devices. The NHP is a good candidate for consideration and development for MEMS.

References

1. Lee, H., and Neville, K., *Handbook of Epoxy Resins*, McGraw-Hill, New York, 1967.
2. Gilleo, K., "What Quiet Revolution?" *Circuits Assembly*, May 2004.
3. Gogoi, B., et al., "Challenges in MEMS Packaging," Proceedings, SMTA International, September 24–28, 2000 [CD-ROM; no pages] Chicago, Ill.
4. Gilleo, K., "MEMS & MOEMS Packaging Challenges," *J. Mat. Processing & Manufacturing Science*, Vol. 8, No. 4, pp. 361–379.
5. Gilleo, K., "MEMS Packaging Solutions," *EP&P*, pp. 49–50, 52–53, 55–56, June 2000.
6. Gilleo, K., "MOEMS the Word," *Circuits Assembly*, pp. 28–31, 33, 34, Nov. 2000.
7. http://www.sandia.gov/ - Enter "MEMS reliability" in home page search engine for several hundred reports.

Chapter

2

Principles, Materials, and Fabrication of MEMS and MOEMS Devices

This chapter will begin by describing and defining micromechanical devices. Micro-optoelectromechanical systems (MOEMS) will be considered as a subset of microelectricomechanical systems (MEMS), and can also be referred to as optical-MEMS. Next, we will examine the mechanisms and attributes of MEMS that serve as the means of classification. Structures and processes for producing these systems will be covered in some detail. Similarities and differences between MEMS and conventional semiconductors will be pointed out. A description of many of the popular devices will follow, including their applications. Throughout the discussion, the reader will be made aware of features that establish the requirements for the specialized packaging required for the various levels of MEMS/MOEMS devices. First, some historical background.

Half a century ago, a critical breakthrough occurred in the form of semiconductors, or solid-state electronics. The first result was the transistor that helped replace the bulky, power-hungry vacuum tube that was all but a dead-end technology despite the Herculean efforts to miniaturize this discrete device. Next, a follow-on breakthrough inevitably occurred, as the transistor was connected at wafer-level to herald modern electronics, enabled by the development of the *integrated circuit* (IC). These tandem breakthroughs brought about incredible miniaturization that continues even today. Similar events have occurred for mechanics, but it's really only the beginning. MEMS is delivering the same magnitude of miniaturization and integration to mechanics by borrowing processes

Copyright © 2005 by The McGraw-Hill Companies, Inc. Click here for terms of use.

born in the electronic semiconductor industry decades ago. Ultimately, MEMS will do for mechanics what the IC did for electronics. Best yet, MEMS can assimilate electronics and combine it with mechanics. And if that were not enough, MOEMS also integrates optics to merge this triad of technologies—electronics, optics, and mechanics—all on a single and truly amazing chip. But MEMS has targeted the replacement of existing products, just like early transistors replaced vacuum tubes to bring smaller, better, and cheaper radios. Now, MEMS is enabling new products based on unique concepts. MOEMS devices that mechanically control light are replacing analog movie and slide projectors that were based on completely different technologies. Older slide and movie projectors relied on photochemistry, optics, and mechanics. MOEMS replaces chemistry with electronics, which allows the all-important transition from analog to digital projection.

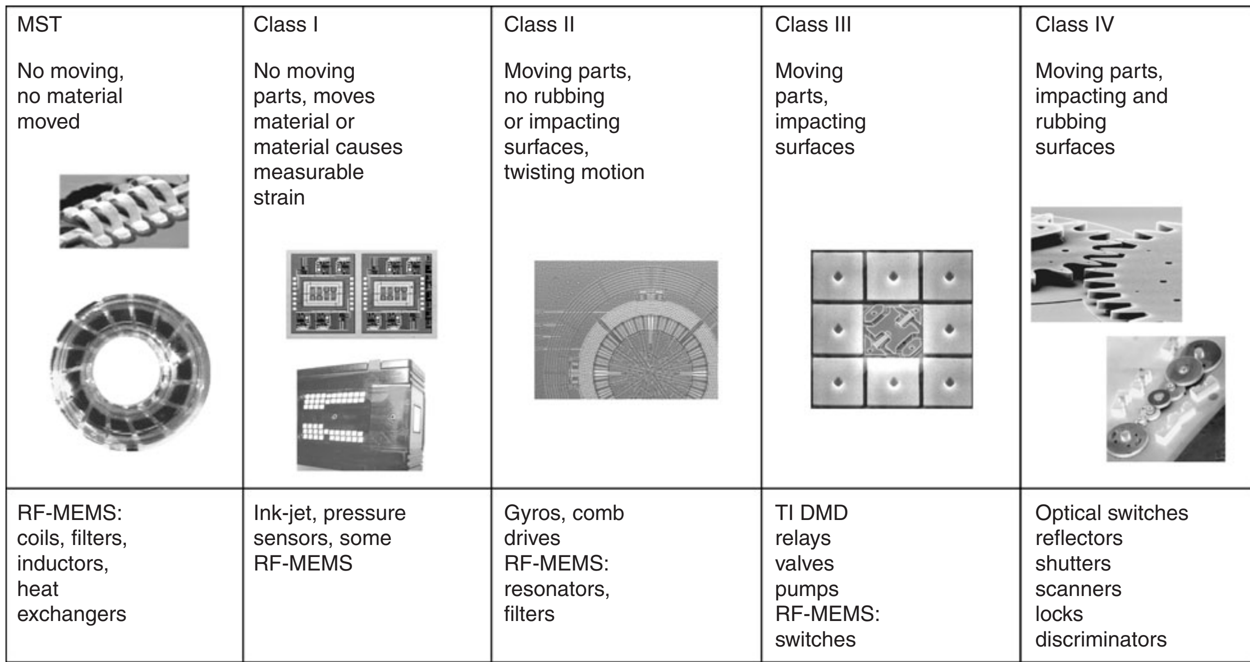
Micromechanical systems have actually been around for almost as long as the IC. In fact, some of the earliest documents describe optomechanical microdevices or *light valves*. Richard Orthuber, for example, filed a U.S. patent on behalf of the U.S. Air Force that described a light projection system based on individually controlled hinged micromirrors made of metal in September 1951.[1] He continued work in this area and filed another patent,[2] with improvements for his light control concept. His system, while not an actual semiconductor device, described all the attributes of MOEMS. The heart of his image projector was a microstructured array, where light was controlled by the movement of individual mirrors. The movement of each mirror was generated by electrostatic force actuation. Electrostatic "engines" are much more effective for tiny devices where the relative surface area is large and mass is low; it remains one of the most common actuation mechanisms for modern electromechanical devices. However, the Orthuber invention relied on a directed cathode beam inside a *cathode ray tube* (CRT) to charge the mirrors instead of a direct electrical signal as is commonly used in modern MOEMS. It was not until 20 years later, however, that the micro-electro-mechanical principle was applied to semiconductor type devices, when Ray Lee, of Texas Instruments (TI), received a patent for micromechanical array of light control mirrors.[3] Today, TI continues to pioneer MOEMS technology, and is clearly the leader in commercial micromirror chips that contain well over one million individually addressed micromirrors. The earlier *digital light processing* (DLP) units were used for airline ticket printers and had only 840 mirrors and were housed in nonhermetic packages that used polymer adhesive seals. The modern TI DLP technology now produces MOEMS chips that appear to be the most complex "machine" ever built. A single DLP chip contains 1.3 million mirrors,

and each mirror assembly can have half a dozen additional parts. All are now housed in full hermetic packages.

2.1 Definitions and Classifications

MEMS can be viewed as a special class of semiconductor type devices, although there are MEMS fabrication processes that do not rely on traditional semiconductor techniques. The most important term in the acronym is "mechanical," but what does it really mean? Mechanical suggests motion and moving mechanical parts. Early definitions required movement within the device itself as exemplified by the early movable mirror patents. Later, motion-detecting devices like accelerometers were introduced, and they all had moving parts that were essential to operation. Today, most types of MEMS devices do have moving parts that are used to sense or control. Ordinary electronic semiconductor devices have no moving parts and the only motion, if we can even call it that, is the flow of electrons through electrical conductors, transistors, and other solid state devices. But the strict definition that requires moving parts for MEMS runs into a predicament with the simplest fluid-handling devices. Ink-jet printers, used by hundreds of millions, employ tiny print head chips to rapidly and precisely eject fluid ink when triggered by an electronic signal. These ink-jet chips are classified as MEMS devices by most of us. The majority of ink-jet chips generate fluid propulsion by heating ink in a cavity using a resistance heater. The microscale used in these chips allows the heater to instantly "boil" the ink causing fluid ink to jet out of an orifice. The ink-jet chip has no moving parts but causes motion. The simplest way to include ink-jet devices in MEMS is to add a class where inanimate devices produce motion. My own inclusive definition for MEMS is microscale (or smaller) devices that move or cause motion in a controlled manner using an electrical signal and/or electrical energy. Note that we require the use of electrons, either as the energy source or signal. While it is possible to construct micromechanical systems that do not use any form of electricity, such as a pneumatic system, these would not fall within the MEMS definition.

There is one more type of device that has some of the characteristics of MEMS but is outside the definition. Microscale passive electrical devices began to appear a few years ago and many were referred to as MEMS. These are various coils, capacitors, filters, and other coil-containing structures with no moving parts. A microscale inductor coil, for example, has no moving parts and does not cause motion unless it is a part of a sound device. It does not even fit the extended MEMS definition. But these *radio frequency* (RF) coils and other devices have some of the MEMS attributes and many are built using the same processes as that



MST	Class I	Class II	Class III	Class IV
No moving, no material moved	No moving parts, moves material or material causes measurable strain	Moving parts, no rubbing or impacting surfaces, twisting motion	Moving parts, impacting surfaces	Moving parts, impacting and rubbing surfaces
RF-MEMS: coils, filters, inductors, heat exchangers	Ink-jet, pressure sensors, some RF-MEMS	Gyros, comb drives RF-MEMS: resonators, filters	TI DMD relays valves pumps RF-MEMS: switches	Optical switches reflectors shutters scanners locks discriminators

Figure 2.1 MEMS/MST Classes.

for MEMS. Yet without the "mechanical" aspect, it really was illogical to include them as MEMS although some tie-in is still desirable. I selected the term *micro-structured technology* (MST) to cover the inanimate microelectro devices. They are really akin to MEMS, but not a true MEMS device. A coil is still a coil, whether it is wound from wire by micromanipulators, or fabricated in a MEMS foundry. All classes of MEMS, with the added MST column, are shown in Figure 2.1—MEMS/MST Categories.

One final caution for definitions—MEMS is not necessarily part of nanotechnology although the media try to group these two areas together. MEMS does quite well on a microscale and there may not be the same incentive to drive down size as there is for electronic chips. In fact, MEMS devices are being produced in older foundries that are no longer competitive in the general electronics area. Some have suggested that once the mechanical device falls into the nanometer range (1 to 100 nm), it could be called *nanoelectromechanical system* (NEMS). But nanotechnology is much more than about size so the NEMS terminology may only cause confusion. Today, microelectronic devices have feature sizes down to 90 nm, and a few have moved to the 65-nm node, but they are not considered nanoelectronics.

2.2 Basic Principles

The two key features for MEMS are mechanical, that can be equated to motion, and electrical. The addition of mechanics or mechanical to an electronic chip gives a tremendous boost to functionality and performance well beyond what one might expect at first glance. The world of mechanics, perhaps the oldest technology, is extremely rich and diversified. Think of all the mechanical equipment in the macroworld and the hundreds of principles used in mechanical engineering. Now think about reducing that world down to chip-size machines. But there's more. The chip-scale mechanical devices, range from meshing gears to sensitive levers, and can be mass produced in massively-parallel processes in existing semiconductor foundries. The ability to miniaturize large mechanical machines and devices to chip-scale with cost-effective processes in existing factories gives MEMS technology incredible power. Most technologists may not realize the full potential of MEMS that will unfold over the next few decades. And if that isn't enough, we can add light and other forms of energy from the electromagnetic spectrum to create a truly incredible convergence of science and technology. MOEMS lets us add optics and physics to the already powerful assemblage. This is certainly the zone in technology where all sciences converge and all can benefit. MEMS is the right size scale for interacting with objects and materials from the macroworld, but also small enough to interact with biological systems. Figure 2.2 is a graphical representation of this convergence concept.

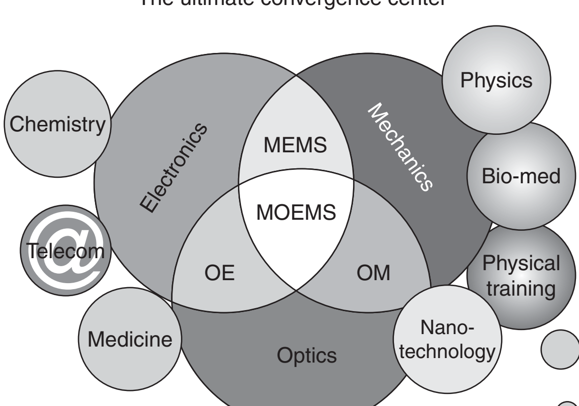


Figure 2.2 Convergence of science and technology.

2.3 Sensing

There are many types of electronic and photonic sensors that can detect everything from pressure to magnetic fields. But the addition of mechanics adds new dimensions and enhances older principles. MEMS technology can mimic all of the human senses and even move far beyond the limited human ranges. The largest class of MEMS devices, approximately two-thirds, fall into the sensor class. MEMS and sensors are often grouped together in technical forums. Some MEMS sensors, like pressure types, are replacing more costly and cumbersome products made from assembled parts. But MEMS are able to do things that were not possible, or were previously impractical. The most important sensor area today is motion detection and measurement. MEMS devices have been used for over a decade to build accelerometers that are used as crash sensors for air bag systems. Today's accelerometers are much more sensitive, but also much more robust and reliable. Accelerometers can now accurately measure acceleration and deceleration in X, Y, and Z directions. However, the two-axis X-Y accelerometer has become very popular and is finding applications in everything from automobiles to toys. Even the new robotic pets, like AIBO (Sony) use MEMS devices to sense and help control movement. But this is just the beginning for motion sensing. There now are commercial MEMS gyroscopes that bring a new level of sophistication to motion sensing. These gyroscopes are not only replacing the older ones built from parts types, but are also able to fit new applications like antirollover systems for vehicles, especially *sports utility vehicles* (SUVs). Many of these sensors have built-in electronics to condition and process information all on the same chip, such as those produced by Analog Devices, Inc. Other important MEMS sensor producers include Bosch, Delsa, Delphi-Delco, Freescale Semiconductor (Motorola), Denso, Infinion, VTI Technologies, and X Fab, who together have

about 90 percent of the MEMS automotive market. There are at least 50 companies designing and/or building basic MEMS sensors, including accelerometers, gyroscopes, and pressure sensors.

2.4 MEMS Sensor Principles

MEMS excels at sensing and it is presently the most important area for development and commercialization. A dozen or more sensing and detection principles are used to measure phenomena associated with mechanical, chemical, biological, electrical, and optical fields. Sensing elements can be made very tiny, extremely sensitive, and redundant for increased reliability, response, and effectiveness. This has all helped make MEMS the preferred technology for sensing in just about every field. Automotive is presently the most important sensing application area for MEMS, but the biomedical field will become the most exciting and sophisticated in due time. Next, we will look at the most common types of MEMS sensors.

2.4.1 Inertial (motion) sensors

The most common motion detectors have moving parts that change their relative position when acceleration, deceleration, and rotational movement occur. There are several ways of detecting and measuring inertial movement. The most popular is the change in capacitance caused by part movement capacitor plate. The MEMS device will typically have a movable spring-loaded plate metallized, or finger, in close proximity to a fixed plate. The spring can be the construction material such as silicon. Although just one pair of capacitor plates will work, it is more common to have an array of plates, or a comb, that is displaced when the MEMS device is moved. The movable comb will have a proof mass and an integral anchored spring that allows a certain displacement to occur under a specific amount of acceleration. The comb and reference plates are typically coated with aluminum to form electrical capacitors. Since capacitance varies as a function of spacing distance, the moving parallel plate design produces a change in capacitance with motion, or more specifically, acceleration and deceleration. Figure 2.3 shows the construction of a capacitative parallel plate accelerometer.

The capacitative sensor design is popular because of simplicity and ease of manufacturing. Most commercial accelerometers use this design in products used for air bag crash sensors. More recently, the capacitor comb design has been applied to two-axis accelerometers where two sets of combs are used to measure motion in the X and Y directions by orienting them perpendicular to one another. Some of these products are sensitive enough to be used in game controllers and other applications where slight movement needs to be detected. Figure 2.4 shows a close-up of the two capacitor comb arrays in a two-axis accelerometer.

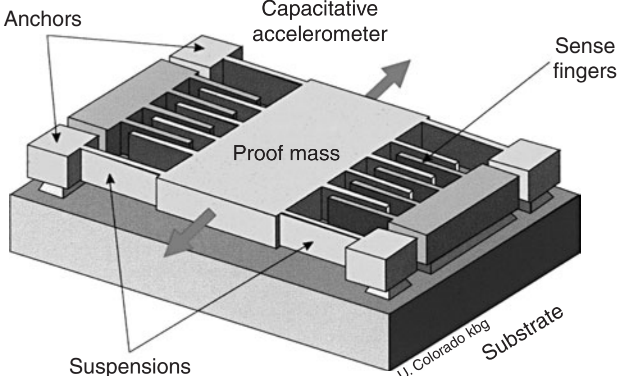


Figure 2.3 MEMS capacitative accelerometer. (*Source: University of Colorado.*)

Several other methods can be used to sense everything from photons to molecules. Principles include piezoresistive, piezoelectric, electron tunneling, photonic, resonance, magnetic, chemical, and biological-biochemical mechanisms. The piezoresistive and piezoelectric effects, where stress changes electrical properties of a material, can be used in pressure sensors. However, after capacitative sensors, only resonance is used to measure motion, pressure, and other forces. A resonator is a fabricator, so it will oscillate at a specific frequency when current is applied. Any change in the material, including effects from pressure, movement, and adsorption of other materials will change the frequency that is being monitored. Resonators can be very sensitive and have several uses. For example, they can be used as radio frequency filters and oscillators.

Multiaxis inertial sensors can be used to measure and analyze vibrations. In fact, if the output of a commercial two-axis accelerometer is plotted with time, the baseline will usually show steady vibrations and

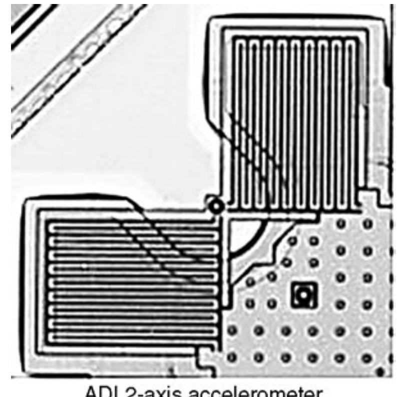


Figure 2.4 Two-axis MEMS accelerometer. (*Source: Analog Devices Inc.*)

random spikes that are due to ambient vibrations that are found just about anywhere. Buildings have countless motors that transfer mechanical vibrations to the building structures. Air conditioners and air makeup blowers are sources of strong vibrations. MEMS sensors can be placed on operating equipment to analyze and monitor machinery. For example, if there is a change in amplitude of an accelerometer mounted on a motor, it may indicate a potential problem like bearing failure. The U.S. Navy, under *defense advanced research projects agency* (DARPA), is sponsoring MEMS research aimed at developing a sensor system for ships that have hundreds of motors. These units could be powered by MEMS energy extractors that will be discussed later.

2.4.2 Pressure sensors

Pressure transducers have been used for decades to measure pressure and provide the output as an electrical signal. MEMS is now replacing many of these older designs that are assembled from many parts. The piezoelectric effect is commonly used, as well as the indirect effect based on piezoresistance. Piezomaterials can be incorporated into the MEMS device that will undergo electrical conductivity changes as they are stressed by pressure. Capacitance can also be used for pressure sensing. A thin capacitor plate must deform, or otherwise move closer to the opposing capacitor electrode when pressure is applied. Likewise, a resonant beam can be configured to sense the force resulting from pressure. Figure 2.5 shows pressure-sensing designs. Pressure sensors add some

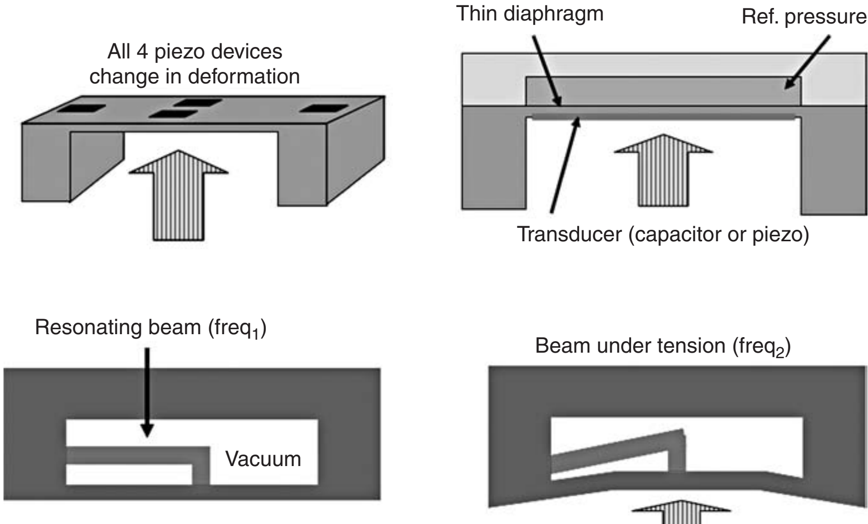


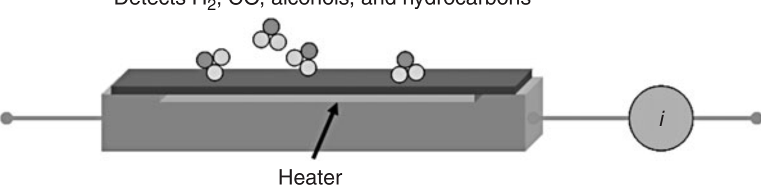
Figure 2.5 MEMS pressure sensors.

level of challenge to packaging, since the force of external pressure must be conveyed to the sensing elements within the device.

2.4.3 Chemical sensors

The ability to detect specific chemicals and even biological agents is one of the most important developing areas for MEMS. Several types are available and more will undoubtedly be developed and announced. The simplest concept uses a surface that will absorb a specific molecule such as carbon monoxide (CO). The absorption changes one or more properties that can be measured electrically, such as a change in conductivity. One design uses a heater beneath the absorber layer, and the heat transfer and temperature lowering caused by the absorbed molecules changes the current flow. It is also possible to build a semiconductor type of device and use the absorbing material as the gate. Another design is called the Chem-FET where the absorber is the control gate. The "mechanical" and "motion" aspects of the device involve the material that moves to the device and coats the sensing element to change electrical characteristics. Both designs are shown in Fig. 2.6. The package must allow gaseous material, and possibly liquids, to make contact with the chip.

There are many variations of the basic Chem-FET but the operating principles are similar. The *ion sensor field effect transistor* (ISFET), can measure the ionic strength of a solution that passes through the device.



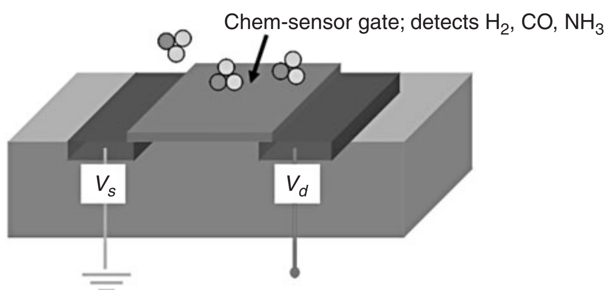


Figure 2.6 MEMS chemical detectors.

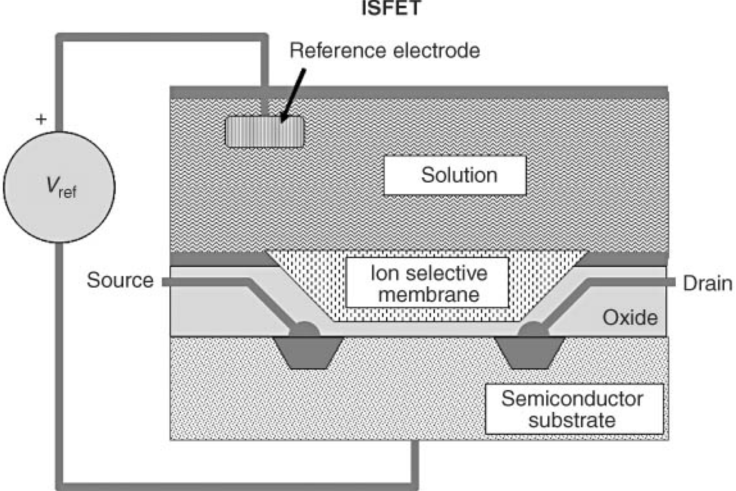


Figure 2.7 ISFET.

The construction must provide a chamber and path for the fluid or an opening for the fluid. The device can be immersed in solution but future designs could have "plumbing" to allow real-time monitoring. The device also has medical applications. Figure 2.7 shows an ISFET construction. Here, the package must allow liquid to surround the sensor.

2.5 Motion Actuation

We have covered sensors that can have chip elements that are moved to external materials and forces. But there are also many MEMS devices that move when an electric current is supplied. Therefore, motion actuation is a key area and one that has seen considerable efforts from industrial, government, and academic researchers. MEMS can utilize essentially all of the *engine principles* found in the macroworld with the exception of atomic energy although some special forms are theoretically possible and have been proposed. But we can add others, such as electrostatic forces that are very efficient at the microscale while impractical at large scale dimensions. Although all MEMS and MOEMS systems use electrons somewhere in the activation process, there can be conversion steps. For example, an electrostatically actuated Internet optical switch can readily use available photons as the primary energy source. The photons, in the form of infrared, can be sent down the optical fiber that normally just carries data and are then converted to electricity to power the switch mirrors. Another clever conversion is to use a mechanical energy extractor that transforms mechanical vibrations into electricity. A MEMS energy extractor, or harvester, is being designed and developed to supply power to various sensors

on Navy ships in the future. The vibrations caused by the ship engines and motors are more than enough to supply these MEMS remote sensing systems. Next, we'll look at specific actuators and then survey their advantages and disadvantages for various uses.

2.6 MEMS "Engines"

Table 2.1 shows the major types of actuators, or MEMS engines, with their attributes. The simplest to design and fabricate is the electrostatic actuator, but there are several different design concepts that can be used to generate different modes of motion, as will be seen in the detailed sections.

2.6.1 Electrostatic/capacitance

The capacitor is one of the simplest and most common passive devices used in electronics. At least two plates are required, and at least one must be able to be charged with electrons. The MEMS capacitor, or electrostatic actuator, is not very much different from the electronic capacitor. Two plates in relatively close proximity are required, so that charging both with electrons causes repulsion force. Alternatively, one can be grounded, or charged positively, while the other is charged negatively to produce attractive forces. When both are charged with electrons, a repulsive force is produced since like charges repel one another. Opposite charges attract, but it is only necessary to charge one plate and ground another to produce a net difference that results in an attraction. These forces can be miniscule in an electronic capacitor, but are still there. But as we scale down the size of a capacitor, the ratio of surface area to mass increases

TABLE 2.1 MEMS Actuator Classes

Actuator class	Notes
• **Electrostatic/capacitive**	

• Linear comb drive
  Rotary comb drive
  Horizontal parallel plates
	Most common very efficient

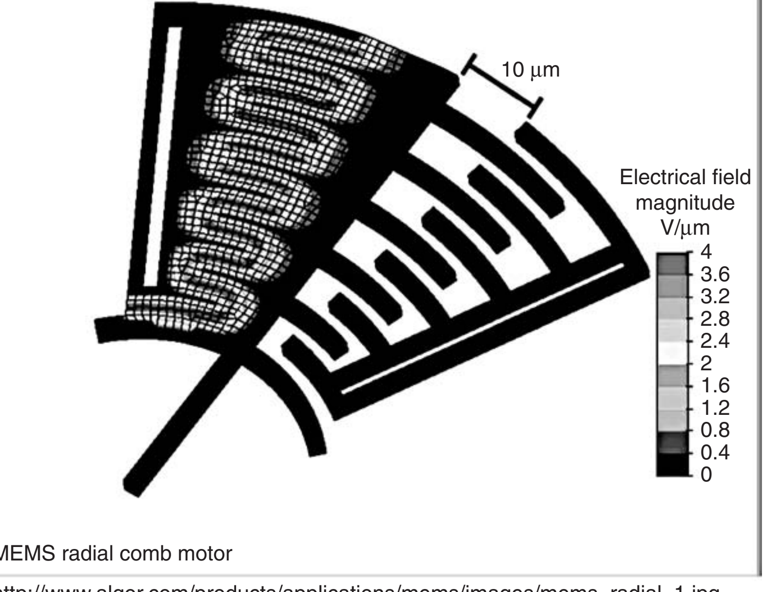
• **Electromagnetic**	

• Linear
  • Rotary
  • Integrated coils or external field
  • Permanent or soft magnetic films
	More compact more complex

• **Thermal**	
• Bimorphic; dissimilar materials • Shape memory alloys	Easy to fabricate
• **Pneumatic/hydraulic**	
• **Mechanical conversions/translations**	

until the resulting electrostatic force is quite significant and very useful. The force is proportional to the capacitor area, the spacing between plates, and the electrical charge. This provides a good trade-off that allows the operating voltage to be reduced, by increasing that plate area or decreasing the spacing. The common approach is to increase capacitor area, typically by adding multiple plates.

The two basic electrostatic motor designs use radial drives and parallel plates, but many different configurations have been devised. Both reciprocal and rotary motion are easily generated. There are many variations however, and a web search will show the wealth of technology. The parallel plate design can be used with pivot mechanisms to produce a rocking, or tilting motion that is useful for optical mirrors. Metallizing nonconductive materials like silicon can easily produce the capacitor plates. Since semiconductor fabs use metallization, like aluminum, copper, and gold, this allows electrostatic actuators to be readily constructed, hence their popularity. While one can calculate actuation force as a result of design change and voltage input, MEMS software makes computations straightforward and automatic. MEMS software is especially useful for multiple plate and radial designs where spacing may be constantly changing. Software can also be used to simulate operation and optimize the actuator design. Figure 2.8 shows software graphical output for a radial actuator under simulation.



http://www.algor.com/products/applications/mems/images/mems_radial_1.jpg

Figure 2.8 MEMS software simulation of electrostatic actuator. (*Source: Algor, Inc., Pittsburgh, PA-USA.*)

There are other designs for using electrostatic force to produce motion. The common parallel plate system can be configured so that the actuator moves parallel to the power plates instead of vertically. This design allows the force to remain more constant since the plate spacing is not increasing as with vertical actuators. Figure 2.9 compares the vertical and horizontal parallel plate electrostatic MEMS actuators.

2.6.2 Electromagnetic actuators

Most of the actuators in the macroworld are electromagnetic. Millions of so-called electric motors operate using electromagnetic principles. These same systems work quite well at the microscale and many such MEMS electric motors have been built. However, construction is more difficult and complex for magnetic systems, and commercial MEMS products have not embraced this form of actuator. Still, one can find countless examples of magnetic actuators from universities and government facilities. These motors can be more compact and powerful than other classes such as the electrostatic. They can also be designed to operate at lower voltage. The electrostatic drives typically run at a much higher voltage—30 to 100 V, whereas the magnetic type can be designed to operate at the single-digit voltages found in electronics power supplies. Motors can have permanent magnets in conjunction with electromagnets, but magnetic material must be used in the fabrication or deposited in the processing. Induction motors don't require magnetic materials.

2.6.3 Bimorphic actuators

The principle behind bimorphic actuators is similar to the thermostat bimetal strip. Heating produces differential expansion that causes bending. A bimorphic arm can be constructed from the structural insulating material, such as silicon, by depositing another material with greater or

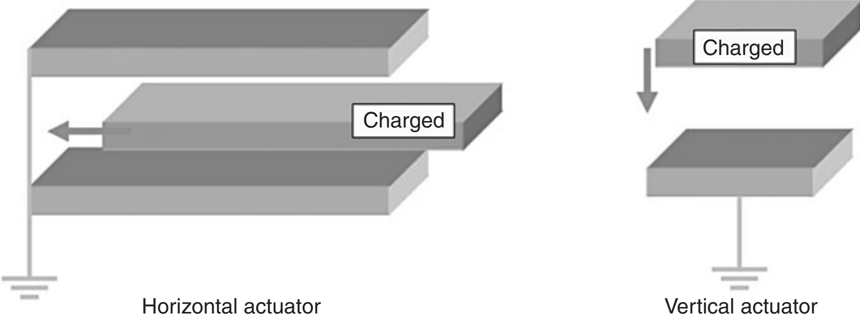


Figure 2.9 Parallel plate actuators.

smaller thermal expansion. One simple and popular construction uses an electrically conductive material as the other substance, so that it can serve as the heating element. Applying electrical power to the actuator arm causes rapid heating and subsequent deformation that is the desired movement. The actuator can be designed as a cantilevered beam that bends when current is applied and this is a common configuration. But there are many other designs. Figure 2.10 shows the bimorphic beam concept.

2.6.4 Piezoelectric actuators

When electrical current is applied to certain crystalline materials, deformation occurs in a phenomenon called the indirect piezoelectric effect. Piezoelectric actuators are used in a few ink-jet printer heads and other jetting devices, but cannot be considered a mainstream technology for MEMS at this time. They are more commonly used as sensors. When certain materials are mechanically stressed, electrical charge is produced by the (direct) piezoelectric effect.

2.6.5 Other actuators

There are many other methods for producing mechanical movement on a microscale, but the most important have already been covered. Others include, pneumatic, hydraulic, chemical, biological, phase change, and several other thermal and photo effects. It is worth mentioning that phase change is an important mode of actuation. MEMS bubble jet type printer heads use this principle, when liquid is converted to gas (water vapor). Chemical actuators may become more important as microturbines and rockets are further developed. Burning of fuel, in either a rocket or turbine, is considered a chemical energy process, since the thermal energy comes from chemical oxidation of the fuel. Under a strict definition, one might argue that, a microrocket or turbine is not a MEMS device, since electricity is not involved.

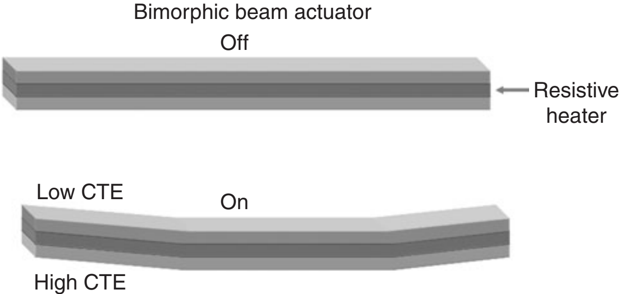


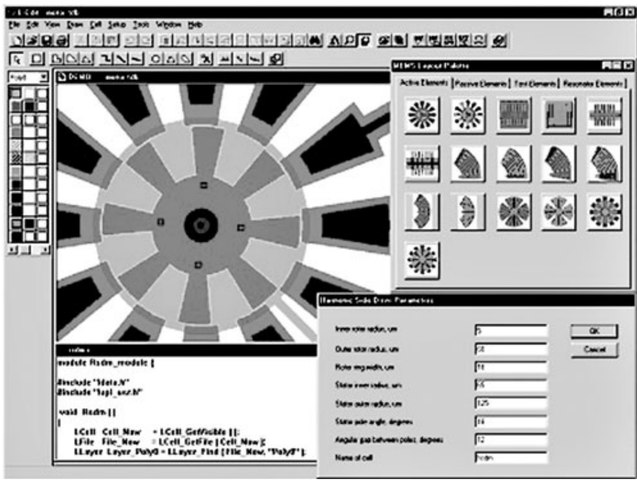
Figure 2.10 Bimorphic beam.

2.7 CAD Structure Library; Building Blocks

MEMS CAD and related software systems have progressed over the past several years to provide powerful systems that include parts of libraries for common functions. Sandia now offers a powerful MEMS CAD suite that is based on its SUMMiT fabrication process. The software has been sent to selected universities that will offer courses and train students, under Sandia's University Alliance Program. However, a significant amount of commercial MEMS software is available that includes MEMSPro, CoventorWare, MEMCAD, SolidWorks, Intellisuite, and others. Figure 2.11 shows a typical parts section library.

2.7.1 Device materials

The choices for structural materials for building MEMS are much broader than for electronic devices and this could become a disadvantage since it makes future standardization more difficult and less likely. The wider use of device materials can also make package design and reliability projections more difficult. The most popular material today is *silicon* and it offers clear advantages. Silicon has excellent mechanical properties at the scale now used for MEMS devices. But more important is the vast infrastructure and knowledge base available for silicon, since it has been the central material in the vast semiconductor industry for so many decades. Employing silicon for MEMS allows standard semiconductor equipment to be used, although some processes are modified.



MEMSPro/MEMSCAP

Figure 2.11 Parts library.

Silicon also allows MEMS devices to be made with integrated electronics, especially *complementary metal oxide semiconductor* (CMOS). Substantial U.S. government funding, primarily at Sandia National Laboratories, has helped develop silicon-based MEMS and to generate data that are useful for understanding performance and reliability, as well as optimizing manufacturing processes. Sandia's SUMMiT process for MEMS is based around silicon, and is arguably the highest-level process available.

However, other materials have been used and will continue to be used. A list is provided in Table 2.2. The table lists sacrificial and permanent structure materials. Note that some fall in both lists and this is determined by the chemistry and processes used.

Some processes require specific materials, and while they may provide special attributes and be more suitable for making specific types of structures, the added choices will hinder standardization and simplification within the MEMS industry. The next section describes and discusses fabrication.

2.7.2 Fabrication methods and strategies

The preferred strategy is to use semiconductor fabrication processes that can be run in conventional fabs with the least amount of modification. MEMS manufacturing processes include photolithography, wet etch (anisotropic or isotropic), plasma etch, *reactive ion etching* (RIE), *deep RIE* (DRIE), *reactive ion beam etching* (RIBE), ion milling, plating, molding, casting, micro *electrical discharge machining* (EDM), laser micromachining, photo resist baking and reflow, wafer bonding, and some

TABLE 2.2 MEMS Materials

Material	Use
Silicon, single crystal; Si	Structural
Silicon, polycrystalline; Si	Structural
Nickel; Ni (electroplated)	Structural
Gold; Au	Structural, conductor, contact
Silicon nitride; Si_3N_4	Structural
Silicon carbide; SiC	Structural
Silicon dioxide; SiO_2	Structural, insulator
Lead zirconium titanate	Piezo; actuator or sensor
Silicon-germanium; Si-Ge	Structural
Germanium; Ge	Structural, sacrificial
Polyimide; Pl	Structural
Aluminum; Al	Structural, conductor
Titanium-nickel alloy; TiNi	Shaped memory metal actuator
Boron; B or BSi	Etch stop dopant, structural
Germanium; Ge or GeSi	Etch stop dopant, structural

wafer-level packaging (WLP). Silicon fabrication methods are the most popular and appear to be increasing in use. The most common method is silicon surface machining that is the oldest and best understood approach. Surface machining is probably the lowest cost method. The process steps are compatible with semiconductor methods and include lithography, formation of sacrificial silicon dioxide, deposition of structural layers, etch removal of the sacrificial areas, stripping of resists, and a final "release" step that frees mechanical components so that they can move. The number of layers can be increased as required for the level design complexity by repeating the structural and sacrificial deposition/formation steps. Sandia's SUMMiT V is a silicon surface machine type process and is capable of producing complex *three dimensional* (3D) MEMS structures, as can be seen by viewing the Sandia Web site. The release step can be performed just prior to packaging.

Another process using silicon is called *bulk machining*. This method uses boron or germanium as an etch stop (retarder) material that is added into silicon by an implanting step. The wafer can be etched using chemical wet methods that etch along crystal planes, or dry plasma processing such as *deep* reactive ion etching (DRIE), that provides straight sidewalls. Metalizing can be applied as required for any of the silicon processes since it is a standard semiconductor step. There are many modifications of these basic silicon processes, as well as others that are fundamentally different. One that is worth mentioning is *lithographie galvanoforming abformung* (LIGA)—the German acronym that designates that it is an electroforming method. This method that forms a precision microtemplate for electroforming metal parts is ideal for fabricating tiny structures made of metal. Coils, inductors, cooling systems, and other metal parts can be made. LIGA, while effective for discrete metal parts, is very limited and not suitable for complex structures with moving parts without an assembly step, unlike the silicon processes that produce "working machines" without postassembly.

One specialized process worthy of consideration is the process for *digital light processor* (DLP) production by Texas Instruments. This microfabrication method uses aluminum. A photoresist is used as one sacrificial material along with metal oxide. Oxygen plasma is used to remove material.

2.8 MEMS Devices

Theoretically, MEMS processes can fabricate, on a microscale, any structure from the macroworld, but we need to be aware that the materials choices are limited. The most common process will only produce structures made of silicon and metal, as well as compounds of both. We can also add silicon-based transistors. However, the secondary process can

add optical materials and even biological agents. Sensors are the most common MEMS devices exemplified by the accelerometer. But the accelerometer has found about 100 different applications and there is no end in sight. The next sections will provide an overview of sensors and controllers before moving into details of specific devices.

2.8.1 Sensors

The single axis accelerometer is one of the earliest MEMS designs. In the past several years, this basic idea has evolved into two-axis and three-axis type devices. Recently, Sandia has announced the world's most sensitive accelerometer that can be used for ultrasensitive yet robust seismic instruments. The simplest accelerometers use a parallel plate capacitor structure as the sensor since it can be made at low cost with silicon fabrication technology. Acceleration and deceleration change the capacitor cell spacing that correspondingly changes capacitance. If on-chip electronics are present, the circuitry can analyze the response and carry out functions such as triggering an airbag deployment system.

Gyroscopes have been developed more recently and commercial MEMS products are commercially available. Analog Devices, Inc. (ADI), one of the leaders in MEMS motion detectors, offers such a product that targets automotive and other areas. The sensitive and versatile gyroscope will be used to signal impending vehicle rollover conditions, and will eventually provide input to a control system that can interact to prevent it. Gyroscopes can sense tilt, motion, shock, acceleration/deceleration, and vibration. From a packaging perspective, MEMS motion sensors present a relatively simple challenge, since no external input/output, other than electrical is needed. However, unless the chip is capped or otherwise protected, a cavity type package is required so that motion is not impeded. But even capped MEMS accelerometers and gyroscopes can be degraded or even rendered inoperable if overmolded. Epoxy encapsulants shrink upon polymerizing (curing) and will cause mechanical stress on the MEMS device. Figure 2.12 shows the ADXRS commercial gyroscope chip from ADI.

Pressure sensors are the next most important area and many commercial products have been announced. Automotive is a natural area for MEMS sensors because of the various pressures that need to be measured using cost-effective, small, and robust devices.

Materials sensors are also important and rapidly emerging. This area has been accelerated, as the need for security and rapid analysis with portable equipment grows with increasing terrorism. A variety of sensing methods have been reported and new strategies are announced regularly. Chemical sensors as well as spectrophotometric types are major classes.

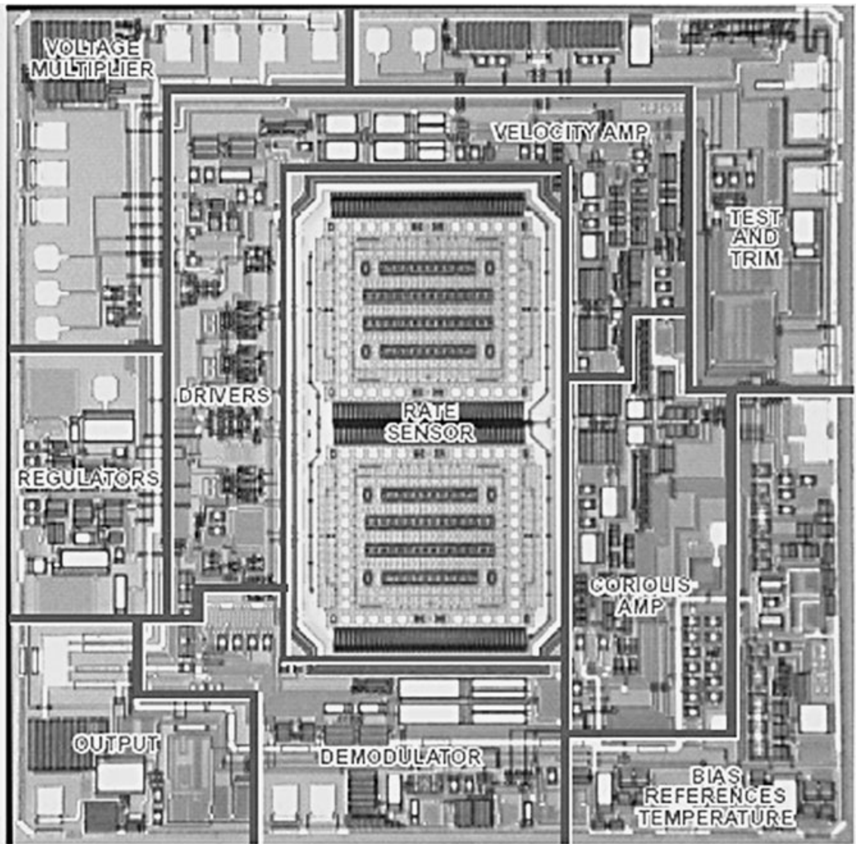


Figure 2.12 ADXRS gyroscope. (*Source: Analog Devices, Inc.*)

Very tiny MEMS proximity switches have been introduced that are less than 2 mm in length. The MEMS products are expected to replace magnetic reed switches and will find many uses in the automotive field.

2.8.2 Controllers

Control is an important and rapidly emerging area for MEMS. Electrical switches and high-speed electronic devices, like RF switches, oscillators, and filters are moving into portable telecommunications products. Major suppliers are Agilent, Infinion, Memscap, Wolshin, Teravicta, and Maggfusion. RF MEMS has come on strong because of the value to cellular phones, and important driver for chips and packages. MEMS antenna controllers, switches, tuners, and combinations, are finding increasing use in cellular phones, telecom-enabled *personal digital assistants* (PDAs), and other powerful portable convergent products. Light controllers are another important area, and these devices are covered in Sec. 2.9.

Pumps, jets, and dispensers. A large number of micropumps have been developed and reported in the literature, and the applications will embrace many fields, although medical and biological areas are well suited.

2.9 Optical-MEMS; MOEMS

The addition of optics lets us move up to optical-MEMS or MOEMS, to bring incredible power and versatility in a single-chip device. Interestingly, the very first micromechanical devices were invented to control light for information display systems. And none other than Alexander Graham Bell, in 1880, used mechanics to modulate light to transmit voice over space in his Photophone; the microphone vibrated a mirror for transmission and a photodetector was used as the receiver. Light control is an ideal application for MEMS, since photons can enter and exit a system without much complexity and photonic packages have been available for decades. The fact that light can pass through hermetic materials like glass, makes light control MEMS even more practical.

Optical-MEMS devices have been designed for two main types of functions—information display and signal control—in the telecommunications field. There are two basic designs for the MEMS light control elements, binary or off/on, and two-axis, 3D "point anywhere." Each system has its own set of challenges, but since the binary devices are easier to build and control, this area has seen the most progress and commercialization. Binary is also the right design for digital displays and TI has a strong position in commercial products due to their early entry and large investments. Their DLP MOEMS chips are now used in all kinds of applications well beyond early use in digital projectors. The other area for MOEMS—signal control—did not really materialize since the telecom explosion and implosion in 2000–2001 reduced development efforts and buying ability of Internet providers. The light signal control concept is a good one and implementation is probably only delayed, until demands on capacity make photonic switching more attractive or even essential. Nearly 50 companies are listed as MOEMS designers and/or fabricators.

2.10 Intelligent MEMS

MEMS designers and developers have debated the merits versus the difficulties of combining logic and mechanics in the same chip. One can argue that it's best to optimize MEMS and electronic designs in separate chips and then mate the two devices later. This is certainly valid when the MEMS process is incompatible with semiconductor fabrication. However, if everything can be built on a single chip, there are manufacturing economics that can strongly favor the integrated or intelligent MEMS concept. ADI has pushed the integrated design for their MEMS inertial sensors and refers to them as iMEMS.

2.11 MEMS Applications

MEMS sensors and controllers are finding new applications on a weekly basis. The proliferation of products will be greatly accelerated by lower cost devices. Many writers have stated that packaging is holding up many applications that are cost-sensitive. Simplifying the package can reduce cost and open up new applications and expand existing ones. Perhaps a MEMS could become as ubiquitous as the electronic devices if we could deliver a MEMS-specific equivalent of the electronic plastic package. Electronics owes much of its success to low-cost packaging used for nearly one trillion units each year. Here are some of the more common and interesting applications.

2.11.1 MEMS sensors; endless applications

Table 2.3 shows a few of the endless applications.

TABLE 2.3 Accelerometer/Gyroscope Applications

Automotive	Consumer	Industrial/scientific/military
ABS/Antiskid	Active subwoofers	Antenna slignment
AC pressure measurement	Ambulatory training	Antenna switches
Air bag deployment	Appliances	Construction leveling
Antirollover detection	Binoculars	Machine health
Battery disconnect	Blood pressure monitor	Equipment tilt sensing
Crash alerting	Camcorders stabilizer	Fork lift positioning
Dynamic suspension	Digital pens	Marine Navigation
Dynamic ride control	Digital cameras stabilizer	Platform leveling
Dynamic cruise control	Disk drive monitoring	Seat damping
Electronic park brake	Game controllers	Seismic Gas Shutoff
Fleet monitoring	Handheld GPS	Satellite dish alignment
Fuel shutoff	Head tracking	Satellite gyroscopes
Headlight leveling	Inertial navigation	Ship mechanical monitoring
Inertial navigation-backup	Laptop antitheft	Shock sensing
Misfire detection	Laptop drop detection	*Unmanned aerial vehicles* (UAVs)
Security/antitheft	Joysticks	*Unmanned military vehicles* (UMVs)
Seat comfort	Mouse-3d	Vibration monitoring
Seatbelt tensioning	Out-of-balance	
Stability systems	Medical devices	
Tilt sensing	Sleep monitor	
Tire motion	Pedometers	
Tire pressure	Sports training–golf	
Transmission monitor	Sports training–fly cast	
Vehicle performance	Sports training–batting	
	Tilt sensing	
	Virtual reality I/O	
	Wearable computing I/O	

Air bag accelerometers. Air bag sensors depend on the accurate and very rapid measurement of deceleration. Since the automotive environment is probably the harshest domain in the high-volume arena, the sensor must be very robust, reliable, and have a long life expectancy. This is an ideal set of criteria for MEMS and is one of the reasons that this application has done so well. In fact, MEMS motion sensors, usually called accelerometers when applied to air bags, are the largest single market for MEMS. Each air bag unit employs two accelerometers for redundancy; both must interpret data as a "crash" and send the "fire" signal before an air bag is deployed. Since more and more air bags are being added to vehicles, the MEMS count average increases each year. Some vehicles with side air bags have eight to ten accelerometers.

SUV gyroscopes. MEMS gyroscopes have recently been introduced and the main target is automotive. These devices are more sensitive and versatile than accelerometers and may replace them in some applications. But the initial target is for antirollover applications and SUVs are a natural focus due to the higher center of gravity. The antirollover system will sense a pending rollover condition and alert the operator, or initiate vehicle slowdown action until the danger passes. Later, more advanced systems could interact with dynamic suspension and be used for sports cars and even in the general automotive field.

More inertial MEMS for automotive. There seems to be an endless array of ideas for applying MEMS to vehicles beyond the air bag and antirollover applications. Self-adjusting suspension is another and one that is likely to be popular. Most, if not all, pressure sensors will likely move to MEMS and many already have. Vehicles also have many positions where pressure measurement can be valuable or even essential. They include oil, airflow in the fuel/air intake, air conditioner, fuel, tires, and more. In the future, MEMS may find substantial use in engines that can only reach maximum efficiency with a high level of sensor feedback. Guidance systems are also short listed. MEMS gyroscopes are already destined to assist GPS for use in cities where buildings block satellite signals. The MEMS guidance unit keeps track of position until signals can be reacquired.

Automotive pressure sensors. MEMS pressure sensors are replacing the older designs built from discrete components. Pressure sensors are used in a dozen applications ranging from engine fluids to air conditioners. Tire pressure monitor systems could be an important automotive market in the near future. In the United States, the National Highway Transportation and Safety Administration, has mandated tire pressure monitoring on all vehicles made after 2006. Trucks are required

to periodically check tire pressure, and with 18 wheels this is a big market. One issue that has been a concern is, the battery life for in-tire sensors that use RF data transmitters. But MEMS may solve this problem with an energy extractor that would convert rotational kinetic energy into electricity.

Consumer products. The consumer product application area is one of the more exciting and interesting markets. MEMS inertial sensors have found their way into game controllers, robotic pets, pedometers, PDAs, cell phones, toys, camera stabilizers, and more. Sony's AIBO "*dog*," uses MEMS to measure paw movement. Once again, affordability will open up applications and further package cost reduction is essential to make MEMS a "must use" device for thousands of other products.

Analyzers. Various types of analyzer schemes can adopt MEMS technology, as the centerpiece or as augmentation. The MEMS device itself can be the sensor, such as the ChemFET mentioned earlier. But more sophisticated analyzers, like spectrophotometers, can use MEMS to move optical elements to allow scanning the spectrum or changing the source wavelength. Biological analyzers can also tap into MEMS technology and concepts such as reactor on a chip could help expedite DNA analysis. Dr. Henry Lee, the noted forensic expert, predicts that portable forensic analyzers will come into use in a few years. This is becoming more practical as DNA analysis becomes more standardized and simplified by new reagents. Preliminary DNA identification time could theoretically be reduced to less than an hour according to Dr. Lee.

Printing; ink-jet devices. Ink-jet printers have become very fast and affordable; thanks in part to MEMS and custom packaging. Jetting devices now boast up to 1000 individually controlled jets on a single chip, and this parallel process design has delivered the extraordinary speeds seen in the latest systems. There are two basic ink-jet mechanisms, heated fluid ejection (bubble jet) and piezoelectric-imparted motion. The simplest mechanism, used by HP and several others, simply relies on electrical resistance heaters that vaporize a small amount of water in the ink and the resulting pressure propels a drop of fluid ink. Some have argued that this is not really MEMS because there are no moving parts. However, most include this simple chip as belonging to MEMS. Our definition used in this book requires that the MEMS devices either move their own elements or add motion to material; we include the bubble devices. The other ink-jet mechanism, piezoelectric movement (as used in Epson printers) certainly belongs to MEMS. Industrial fluid jetters that dispense chemicals, molten metals, and electronic materials, typically

use the piezo type of head since it is faster, more controllable, and can generate more pressure faster. Over 50 companies claim to manufacture MEMS fluidic devices but products range from simple ink-jet chips to more complex bio and chemical-MEMS types.

Safety. Accelerometers have been designed into control systems that need to be shut down during earthquakes. One unit turns off natural gas to premises when an earthquake signature is detected. The concept is being applied to other systems such as gas stations, where fuel sources need to be shut down.

Control systems. A variety of control systems can be envisioned where fluids, gases, and even solids are regulated. Even mechanical motion from the MEMS device might be used to cause other systems to be controlled. In the future, we will see all kinds of pumps with reservoirs, sensors, and control valves that will find use in analytical equipment, small engines, dispensers, medical equipment, and personal medication such as insulin pumps, fuel cells, microwashers, microturbines, rockets and coolers.

RF-MEMS. The *radio frequency–MEMS* (RF-MEMS) application area is ripe for expansion and exploitation. The technology has had its share of issues including cost and reliability, but these areas appear under control and improving. MEMS RF switches have excellent characteristics such as an insertion loss of about 0.1 dB and high isolation. One key technology for many devices is the ability to change capacitance quickly by introducing an electrical control signal. A variable capacitor can find use in all kinds of radio and communications circuits. Typically, capacitor plate distance is varied in the MEMS device. Resonators can be made by adding the MEMS capacitor to an inductor to create a tuner or oscillator. Variable filters can also be produced, since most are based on variable capacitors. At least 20 companies claim to be in the RF-MEMS business.

Energy devices. Several ingenious ideas for producing and extracting energy using MEMS have been developed and described. Some interesting work has come out of Massachusetts Institute of Technology (MIT) under government grants. One is the microturbine that could eventually lead to tiny power units to power portable devices using a variety of fuels not compatible with fuel cells. Figure 2.13 shows a diagram of the MIT fuel-powered MEMS-like turbine. Some would argue that this is just a very small engine and there is no true electrical or electronic feature and they may have a good point. But the MIT energy harvester or extractor, however, is clearly a MEMS device. The concept is to use ambient mechanical vibrations and convert them to electricity. This would enable

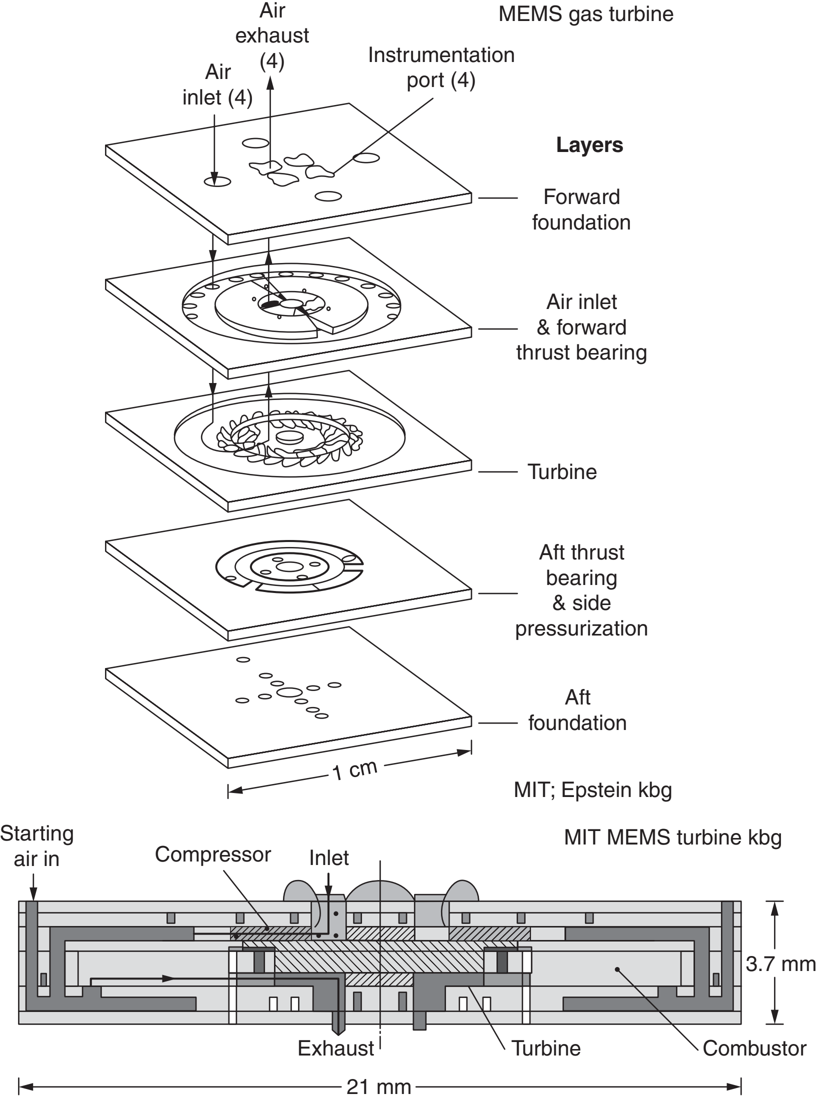


Figure 2.13 Turbine. (*Source: MIT.*)

remote devices to be powered indefinitely. A MEMS vibration analyzer, could be powered by a MEMS energy device and placed on motors or on various pieces of factory equipment. The original intent under the navy contract was to develop remote power for shipboard sensors. Adding RF signaling could lead to very versatile monitoring systems.

Propulsion and locomotion. MEMS devices, by our definition, have elements that move or cause motion of materials. MEMS RF switches are an example of the first category, while the ink-jet is a good example of the latter class. MEMS devices can also propel themselves. While there are many "lab" examples not designed for commercial use, such as the walking MEMS chip from the University of Wisconsin shown in Fig. 2.14, there are others that are intended for specific applications. But most are tethered devices connected to power and control wires. The microrocket motors from MIT and California Institute of Technology may eventually be used in microsatellite position control. These rocket engines will not require packaging in the traditional sense since the device itself becomes the package. Other propelled MEMS include airborne or MEMS "flies" that are now only in a rudimentary stage. MEMS wings have been developed and tethered devices are in testing, but it remains to be seen if enough energy can be carried for an independent flight.

Synthesis (on chip). MEMS fabrication techniques allow chambers, mixers, valves, and pumps to be crafted, as well as other parts that can be used to build a tiny chemical reactor or even an entire microfactory. Heaters and sensors can be added, so that complex chemical reactions can be initiated and controlled to produce products. These MEMS systems can eventually allow practical synthesis on a chip that will find important uses in medicine, analytical areas, and limitless applications that have not yet been thought of. Devices for synthesis of drugs, or pharmaceuticals have

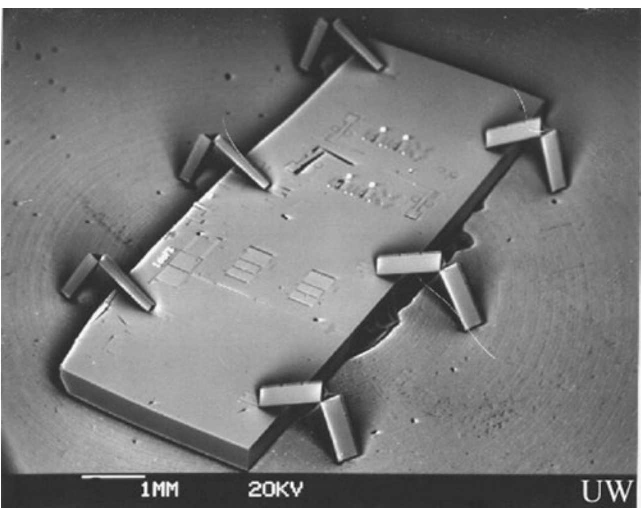


Figure 2.14 MEMS walking device. (*Source: University of Wisconsin.*)

been referred to as Pharmacy-on-Chip, although the term is also applied to chips that will dispense drugs (see "Drug Delivery" below).

Drug delivery. There are many university research programs aimed at developing very small drug delivery systems. Many use semiconductor fabrication methods and are generally classed as MEMS, but not all meet our criteria. For example, a silicon chip that contains drugs that slowly enter the body by natural processes like dissolution, osmosis, and others, but has no electrical input or control, is not MEMS in the strict sense. These are really time-release systems typically based on well-known rules of chemistry and physics and do not rely on MEMS principles. Some are contact devices and others are implantable types. Those devices that are designed to utilize active injection and have logic control with timing would be true MEMS. But at this point, most of the efforts are directed toward passive, time release. However, the University of California at Berkeley has built a wearable system with reservoirs, channels, pumps, and valves that are shown in Fig. 2.15. At least 18 companies are thought to be involved in biomedical MEMS work.

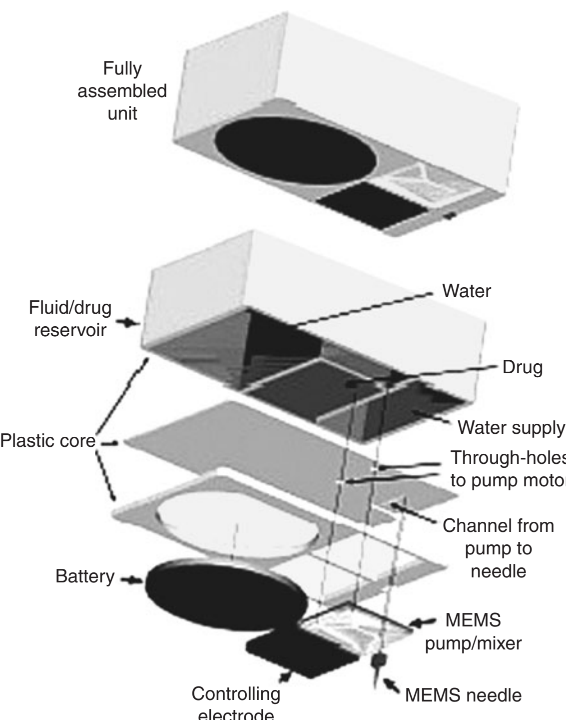


Figure 2.15 Berkeley drug delivery. (*Source: University of California-Berkeley.*)

Military. The military is a big customer for MEMS, and this is why Sandia National Laboratories has such a large MEMS budget. Inertial sensors are presently the most advanced and are found in everything from UAV to tanks. The Inertial Measurement Unit (IMU) is a core system based on MEMS technology and is combined with a GPS receiver. The IMU comprises three gyroscopes and three accelerometers linked together in an inertial guidance system. MEMS subcomponents are used extensively. The system package is the full *hermetic* class. In some cases, the package is made up of outer chamber halves that are sealed together to enclose the various subcomponents, including the MEMS devices. *Joint Direct Attack Munitions* (JDAM) employs guidance units that can be retrofitted to old-fashioned gravity bombs, providing steering by means of movable fins. These units use IMU and therefore contain several MEMS devices. The packaging is also high-reliability full hermetic. IMU is used almost everywhere that guidance is important and that now includes ground vehicles. Tank guns are kept on target with such guidance systems and the principles are similar to digital camera jitter control. Ground vehicles are being fitted with MEMS gyroscopes that signal rollover hazards, and the systems are not all that different from the antirollover units now moving into SUVs. The size of the guided missile continues to shrink and even larger caliber bullets are potential areas for MEMS guidance.

RF-MEMS is another important technology for military communications, and especially phased-array radar systems. A single radar unit can use 500,000 MEMS switches. This radar system, using electronically controlled multiple beams and frequencies can scan more rapidly and accurately and will be used for detection and weather monitoring.

Biomedical MEMS; detection, analysis, drug delivery, repair. Biomedical MEMS or Bio-MEMS, will have a very significant future, but progress will be slower due to the greater complexity of such systems and the need for extensive long-term testing. We have already covered synthesis and drug delivery, but analysis and detection are moving ahead, perhaps even more rapidly, since they can be viewed as laboratory equipment instead of medical products. One of the most intriguing concepts is the MEMS DNA and bio-material detectors that are being pioneered by IBM, small start-ups, and many universities. The IBM device is composed of very thin, flexible silicon cantilevered beams that measure deflection caused by absorption of DNA and other biochemical materials. The cantilevered beams are coated with different biologically-active reagents that selectively adsorb biological materials. The formation of chemical bonds between the agents and biomaterials bends the levers out of plane creating stress that is detected. The present MEMS device can detect up to 250 (number of beams) different biomaterials, quickly and automatically. IBM's latest system operates on a resonance frequency principle. The tiny cantilevers, 500 μm long, 100 μm

wide, and about 1 μm thick, resonate at a frequency of about 4 kHz. When molecules are adsorbed on a surface of a cantilever, a change in surface stress occurs, that causes the cantilever to bend and reduce the frequency, and this is measured as a response. Cantilevers can also be important in exploring the physics and chemistry of the nanometer world.

2.12 MOEMS Devices—MEMS Plus Light

Light control and analysis are two of the most important principles used in technology today. Most of the information we receive is conveyed by photons. Sight is our most sophisticated sense. A large percentage of our most advanced analytical techniques use light in some form. While the term *light* means visible in the strict sense, we will use it to include the general photonic spectrum that includes infrared and ultraviolet, but will exclude photons in the radio section of electromagnetic waves. MOEMS or optical-MEMS is one of the big success stories for micromechanical technology and it is really just beginning.

2.12.1 Light control principles

The earliest light control microelements used electrostatic forces, as do most of today's modern MOEMS devices. Electrostatic actuators are simple and effective, although they may require a higher voltage than magnetic types. The single-axis mirror element is the most popular device since it is the right configuration for digital projectors. A vast array of micromirrors either points toward the lens (on) or away (off). *Texas Instruments* has shipped more than one million MOEMS DLP chips and its use is finally accelerating after many slower growth years. Figure 2.16 shows a detail of the TI mirror array and actuator that can be seen by removing one

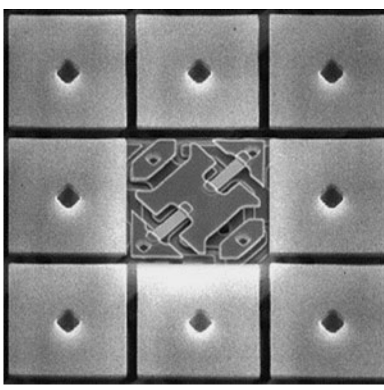


Figure 2.16 TI DLP mirrors with one removed. (*Source: Texas Instruments.*)

mirror. The package is presently a full hermetic ceramic design with a bonded glass lid. Figure 2.17 shows the construction of the package. Getters are used to absorb moisture and to trap particles. A single particle including one that was the result of wear, could disable a mirror to cause a "dead" pixel. However, the shaft upon which the mirror rotates is actually a torsion bar and there are no rubbing parts.

Two-axis 3D types may be better suited for switching applications such as Internet routing. Although there are dozens of mirror configured devices, there are other possible mechanisms. Agilent developed a completely different control principle, based on moving an optical fluid into the light path. There are actually no moving parts, just like the inkjet devices upon which the *bubble switch* is based. The system has been demonstrated on small networks. There are still other control principles, such as *mechanical antireflective switch* (MARS) from Lucent, which operate on a wave interference principle, and deformable mirrors from Boston University. MEMS has also been used to move diffraction gratings that can be used to change output color or to scan the spectrum. The variable diffraction grating is well-suited for spectrophotometers.

2.12.2 Applications for optical MEMS (MOEMS)

Projectors. Most have seen and used digital projectors that have now become the standard way of presenting. While *liquid crystal display* (LCD) light valves can be used, the lightest, brightest, and smallest projectors use MOEMS from TI, although many other companies have introduced MEMS controllers to try and capture a share of this large and growing market. The TI MOEMS chip consists of an array of tiny (16 μm) square mirrors that are individually controlled by electrostatic charges. The standard chip, slightly larger than 1 in on a side, contains about 1,300,000 individual mirrors that can move rapidly enough for videos and never fade since light is reflected off a nontarnishing surface.

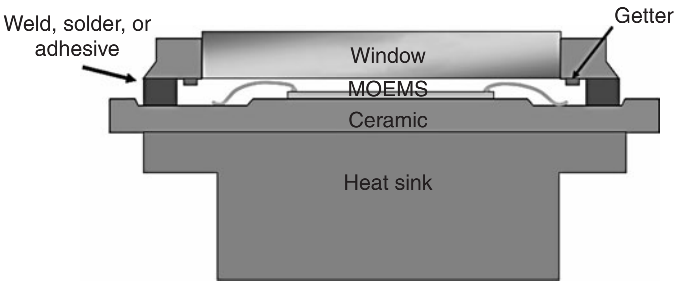


Figure 2.17 TI DLP package cross-section.

An extraordinary amount of research, some at universities, has been done on the DLP chip.

Cinema. Digital cinema is advancing at a modest rate and many theaters across the world use a MOEMS-enabled projector. Texas Instruments pioneered this area many years ago and is the leader today. Their projection system has been used at Academy Awards ceremonies and has even won an award. The same basic MOEMS concept, as used for small business projectors, has been adopted for cinema but in a ruggedized system that can take the abuse of thousands of lumens of light with all the by-product heat. The original lighting source used for film projector is retained and a digital projector head, shown in Fig. 2.18, is retrofit. Digital movies are brighter and crisper, and they allow new effects. The big payoff is that the medium is digital instead of relatively expensive chemically processed photographic media. Eventually, movies will be sent via the Internet or even by satellite with substantial savings.

High-definition television. There are several technologies that can be applied to high-definition television (HDTV), and they include plasma, LCD, and MOEMS. The MOEMS approach could have the best economics for larger screens because of the optical scalability. All systems that are integrated into the screen require more material for each pixel increase. But MOEMS is a projection system and the screen size involves optics, neither more screen material nor more electronics. TI launched products with several companies, but Samsung has been the most

Figure 2.18 Digital cinema projector. (*Source: Texas Instruments.*)

aggressive, offering several sets in different sizes. All use a MOEMS chip and back projection. Brightness should be more constant but can be rejuvenated with a new light source. Color intensity should not fade since it is optically derived and there are no phosphors to degrade. Time will tell if MOEMS will become the leader. Many other companies are expected to commercialize MOEMS-TV in the near future.

Internet. The Internet bubble expanded quickly several years ago as dot coms proliferated, service providers added capacity, and advanced equipment makers pushed technology to the limits. The long-haul links of the Internet that connect cities together are essentially all photonic with data traveling over optical fiber. But switching must occur at nodes along the way so that e-mail and web pages are routed to the address indicated in the packets. But the routers are electronic and are built around microprocessors. This means that the photons must be converted to electrons to be routed and then into photons again. This happens at every router so that an e-mail can go through a dozen or even two dozen double conversions. A more ideal switching scheme would deal with photons directly. The switch would almost certainly be based on MOEMS technology. One could use a binary switch based, such as the DLP just discussed, or a two-axis type that may be better suited. But just about the time that many MOEMS switches had been developed and were even being tested, the Internet bubble collapsed and the electronic routers survived as the standard technology. But today's Internet growth, although slower than the out-of-control years at the beginning of the millennium, is steady and real. Eventually, traffic will be high enough, profits large enough, and the return on investment good enough, to move to MOEMS direct switching and routing. MOEMS Internet equipment will almost certainly have a future, but the timing and size are hard to predict. Figure 2.19 shows a 3D mirror and Fig. 2.20 shows how the switching would work.

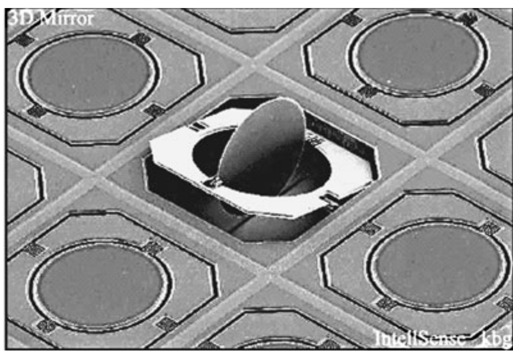


Figure 2.19 Two-axis 3D MOEMS mirror. (*Source: Intelli Sense, Inc.*)

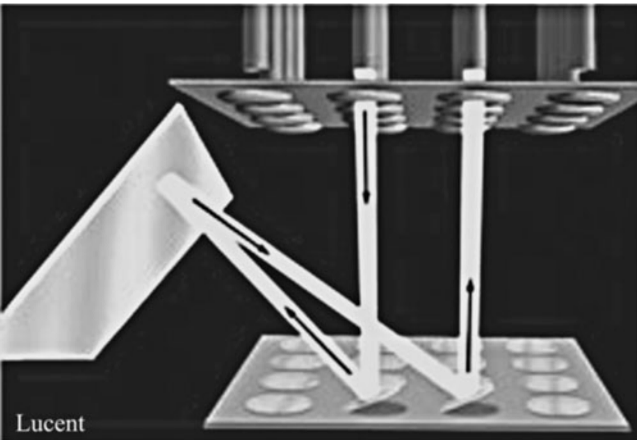


Figure 2.20 Internet photonic switching scheme. (*Source: Lucent, Inc.*)

Spectrophotometers. Handheld spectrophotometers are now available and are even pocket-size—thanks to MOEMS. A tiny MOEMS spectrophotometer that plugs into a laptop or PDA is on the market too. The SPV10 spectrophotometer, from Nomadics, is self-contained and connects to the PC card slot without cables or external power supply. A broadband light source, user-configurable sample holder, diffraction grating, photodiode array, and interface circuitry are all enclosed within the unit. The instrument collects visible spectra from samples held in standard cuvettes. This MEMS-enabled product is one of the many that will boost micro-opto-mechanical technology. This spectrometer requires less than 50 mA while operating and can draw required power from a laptop or the PDA. Figure 2.21 shows the plug-in unit.

Figure 2.21 MEMS spectrophotometer. (*Source: Nomadics, Inc.*)

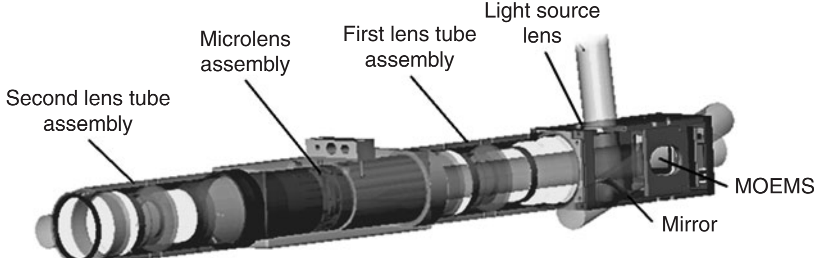


Figure 2.22 MOEMS image placement projector. (*Source: Ball Semiconductor Corp.*)

Security. MOEMS is being applied to security in the form of portable analyzers, such as spectrophotometers, designed to identify specific hazards. Very sensitive infrared imagers have also been developed that could be used to detect the heat from people hidden behind walls and in transport vehicles. MOEMS light beam transmitters are now available that have been used to transmit photonic data signals to transceivers including personal computers. This type of system might also be used to beam designate personal targets for apprehension.

Imaging for manufacturing processes. There are many industrial processes that require image placement, and they include IC fabrication and *printed circuit board* (PCB) manufacturing. While ICs require extreme resolution that increases every year, PCBs require a more modest feature size and a much lower resolution. A MOEMS artwork imager/projector has been developed for imaging PCB conductor traces and solder masks. The heart of the image placer is TI's DLP chip. This hardware from Ball Semiconductor would appear to be a good choice for prototyping and small runs. Figure 2.22 shows the MOEMS-based image projector.

Biometrics. MEMS can be used to measure specific features of the human body. This area has become important for security personnel identity verification. However, optical imagers and even touch screen technology can also be used, and may be lower in cost and more applicable.

2.13 Summary

MEMS is an old but new field of technology, and it is really embryonic, based on what we can expect to come. The majority of MEMS devices are fabricated using modified semiconductor methods. The surface machining process can be used to fabricate micromechanical devices from silicon and it is compatible with CMOS. This allows conventional electronic devices to be fabricated on the same chip, so that mechanical

features and electronics are integrated. Various actuation mechanisms are available to move MEMS subelements but electrostatic activation is simple and popular. The addition of optics to produce MOEMS devices adds a final dimension of technology that yields considerable versatility. The MOEMS DLP, with 1.3 million mirrors, may be the most complex machine yet built. MEMS/MOEMS will continue to expand until it has been embraced by virtually every science and technology. MEMS is a suite of technologies that can be viewed as a grand convergence with extreme densification and extraordinary ramifications. However, major developments in package will be necessary, if MEMS and MOEMS are to achieve full potential.

References

1. Orthurber, R., "Color Television Projection System," U.S. Patent 2,681,380, June 15, 1954.
2. Orthurber, R., "Method of Preparing Electrostatic Shutter Mosaic," U.S. Patent 2,749,598, June 12, 1956.
3. Lee, R., "Process for Fabricating a Panel Array of Electromechanical Light Valves," U.S. Patent 3,600,798, August 24, 1971.

Chapter

3

MEMS and MOEMS Packaging Challenges and Strategies

Microelectromechanical systems (MEMS) devices add at least one special requirement to the package that is not usually required for nonmechanical devices. MEMS chips typically have moving parts, or these devices cause materials to move, and the package must be designed to accommodate these mechanical actions. *Micro-optoelectromechanical systems* (MOEMS) add a further requirement to mechanical activity; optical or photonic transmission is required to and from the chip. Photons must have access to the MOEMS device by means of a free path (free space) or by way of photon conduit such as an optical fiber. Most MEMS and MOEMS devices may also have specific requirements and limitations on the makeup of the atmospheric constituents within the package, especially moisture content. Although MOEMS devices might appear to present the greatest challenge to packaging, those devices that require access to actual materials have even greater needs and will require new concepts in microplumbing and in package routing of materials. This chapter will begin by examining the special challenges while suggesting strategies and concepts. Evaluation methods will be described and discussed where appropriate.

3.1 Product-Specific Character of MEMS Packaging

We can group MEMS into two broad categories—devices that have moving parts and those that produce motion in materials or mechanical action in other devices. The first type of device in the motion class will generally have exposed moving parts on the active face of the chip. A subset of motion

Copyright © 2005 by The McGraw-Hill Companies, Inc. Click here for terms of use.

devices will have moving parts that are internal and protected before final packaging, and these will include chips that are enclosed or capped at wafer level. Today, capping is popular and well established for inertial devices that do not require nonelectrical inputs, but capping can become more sophisticated in the future to accommodate MEMS devices that use external materials. Some MEMS units that are assembled after fabrication by wafer-bonding or assembly of discrete parts, like pumps, can have moving parts within the structure that are protected by the device itself. The device becomes the package. Others that normally have active surface elements can be protected by caps or other types of enclosures that are added at wafer level, or even chip level. Caps can be considered part of the package and such processes are referred to as zero-level packaging since they occur before chip connection, or first-level assembly, or level 1 processing. We may prefer to classify capping as a prepackaging step since it may not even be handled in the packaging foundry.

Devices with exposed moving parts obviously require free-space packaging designs but there are only limited choices at this stage of MEMS package development. One possible exception to free space would be the enclosure of the device in fluid or gel that still permitted the MEMS chip to function. This strategy has worked for pressure sensors that will still function after encapsulation with a hydrophobic but very elastomeric gel or low modulus polymer. We can note that even those MEMS devices with caps and no external or exposed moving parts can function better in cavity packages where there is no stress due to contact with an encapsulant or a molding compound. Direct contact with packaging material, especially thermoset polymers that will shrink, will generally add stress that affects the device and can degrade performance. MEMS chips are orders of magnitude more sensitive to stress than electronic chips. Since many MEMS devices need free space, or cavity style packaging, we will include this feature as a standard requirement for MEMS and MOEMS. Probably all devices, even those that are capped, will function better in a cavity package.

3.2 MEMS General Packaging Requirements

3.2.1 Free space (gas, vacuum, or fluid)

Free-space packaging is sometimes referred to as an air, or air cavity, package. We will use the term cavity package that is less restrictive since the cavity may not contain air but will still have a cavity configuration. The original packages used for *optoelectronic* (OE) devices and early electronic systems were all free space and fully hermetic vacuum structures, still considered the best packages. The world's first packages were made of glass since it was well understood, widely available, and

easy to work. Later, vacuum packages were made from metal, ceramic, and combinations, although glass was retained for display products. Early hermetic packages have been described in Chap. 1 in some detail.

Today's offerings for cavity-style, nonoptical packages include two mainstream materials—metals and ceramics. Polymer-based near-hermetic packages that may be engineered to fully hermetic are just emerging. Metal cavity packages can be used for MEMS, MOEMS, and nondisplay OE devices as well as complete module assemblies. The metal package can be made in almost any size, but the shape is typically confined to a rectangular boxlike configuration since this is the easiest to manufacture. An exception to the rectangular shape is the cylindrically formed metal can style package such as the *transistor outline* (TO). This older hermetic design is still in general use today and is probably the lowest cost metal-hermetic package available. However, although the TO is a cavity fully hermetic package at reasonable cost, it has limitations in terms of size and the number of *inputs/outputs* (I/Os). The TO style package, shown in Fig. 3.1, has not been widely adapted for MEMS or MOEMS, although a few discrete OE components, such as diode lasers, have been packaged with a slightly modified version of the TO. But the TO should still be considered for MEMS. This package achieves a decrease in cost because it is automatically stamped and formed out of metal instead of machining from solid metal blocks commonly used for most other metal packages. The world's most cost-effective metal-hermetic package is probably the *lowly beverage can* that is produced at a rate of millions a day from slugs of aluminum that are pounded into cylinders at a speed that nearly liquefies the metal. The low cost was achieved because of standardization and the market motivation for this large market. The TO package shares some traits with the beer can and appears to be the only metal-package configuration that can be economical.

The package-making process generally dictates the total cost not the materials. Most metals are inexpensive except for a few such as gold and palladium, and a $500 metal-hermetic package for optoelectronic

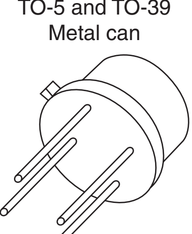


Figure 3.1 TO package.

transceivers, for example, may only have a few dollars of material content. So as we examine package options for cost reduction, the process steps will be the primary consideration. This also means that metal-hermetic packages can meet our low-cost targets—but only if we adopt the right processes. Metal-shaping processes include mechanical machining, laser machining, chemical etching, stamping, and all kinds of forming, power molding, injection molding, powder molding, casting, electroforming, and several others. The most cost-effective metal-working processes can require large machines and substantial tooling as short runs are impractical. But the use of metal enclosures for electronic packaging requires adding a dielectric material so that electrical connections can be brought through the metal enclosure. This is sometimes referred to as the "pass-through" in metal packaging. The insulating material must be compatible with the metal in terms of bonding and thermal expansion and must provide hermeticity.

The conjoined metal-dielectric system must not degrade during thermocycling that will always be required as a package criterion. Metals have an intermediate *coefficient of thermal expansion* (CTE) value; for example, copper is about 18 ppm/°C. Ceramics and glasses, the most common dielectrics used with metal packages, generally have values that are much lower, thus creating a thermomechanical mismatch. This mismatch can cause stress during thermal cycling that will destroy a material or cause debonding, cracking, and leaking, or simply cause destruction of the package. Specially formulated glasses are often used to create the pass-through insulators for metal packages. Lower expansion metal alloys are also employed, like Alloy 42 (Kovar). Material sets have been developed, tested, and established over many decades, however. It should be noted that once the device is assembled into the package, a lid must be applied to finally enclose the system. If the lid is metal, it must be soldered, brazed, or welded for hermeticity and the device must be able to tolerate the lidding process. Localized heating can be used, including laser soldering. Lids can also be bonded with polymeric adhesives, but the result will not be hermetic. When all these constraints and processes are taken into account, the challenge in using metal for low-cost cavity packages has some high hurdles.

Ceramic materials are also commonly used to make cavity packages as well as open or exposed packages that are very popular for *central processing units* (CPUs) that utilize flip chip or *direct chip attach* (DCA). Ceramic cavity packages are generally produced at lower cost than their metal counterparts, partly because they are very good dielectrics. But their electrical nonconductivity requires that conductors be added; just the opposite of the situation with metals. However, it is relatively easy and inexpensive to add patterned metal to ceramic

by using long-established circuitry processes. Since metal conductors can be added in high-density multilayer configurations, ceramic packaging technology enables complex routing and multiple devices that can be placed and connected within the package. Ceramic processes offer more options than metal enclosures, and there has been considerable development in the materials and circuitry process and the work continues today.

Ceramics were first used in high volume well over half a century ago in World War II proximity fuses. The electronic detonator fuses were based on hybrid circuits that utilized screen printing of metal-containing inks onto flat ceramic substrate—alumina (Al_2O_3). These circuits were enclosed but did not require hermetic packaging because vacuum tube electronics was used and the low-density circuitry with noncorrosive materials did well. Of course, shelf life for World War II bombs was not an important consideration. This war effort "print and fire" technology is still used today for making circuits and packages. Processes that can be used for ceramic cavity packages include screen printing, punching, laser machining, mechanical machining, casting, molding, and a few others.

Other materials could probably be used to fabricate cavity packages, but polymers are the next most likely choice for further examination from a low-cost and process-simplicity view. Plastic processes can also produce extremely intricate and precise parts. Plastic packaging will be covered in much detail in a section devoted to this topic.

3.2.2 Free space (fluid)

A MEMS device could conceivably be immersed in a liquid and still function. In fact, MEMS pumps require fluid. But there may be benefits to placing a MEMS device in a dielectric fluid even if it is not a pump. The fluid could dampen motion, if that was desirable. But it could exclude contamination including moisture, if hydrophobic fluid like silicone or fluorocarbon were used. A fluid could also provide a lower dielectric constant and assist in heat transfer. But a MEMS sensor designed to measure fluid properties, such as viscosity, could be surrounded by liquid during use. This would eliminate any package requirement for hermeticity but a more complex design could be needed if fluid is to be pumped in, or circulated through the package. Filtering or some other separation techniques could also be needed. However, if the liquid sample was electrically conductive, then the electrical interconnect would need to be isolated. This is done with ink jet packaging where the chip and electrical connections are isolated from the fluid reservoir. Figure 3.2 shows some chip-in-liquid packaging concepts.

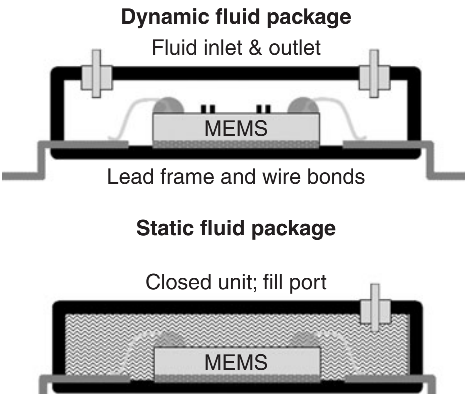


Figure 3.2 Chip-in-fluid packages.

3.2.3 Low contamination

Low contamination is considered important for nearly all packages, but it can be critical for many types of MEMS and nearly all MOEMS devices. The Texas Instrument *digital light processor* (DLP) MOEMS device that contains 1.3 million micromirrors can be ruined by one tiny particle that obstructs any one of the millions of parts that move the 16-µm mirrors that are closely spaced on 17-µm centers. But the contamination problem is more complex and difficult than may appear, since extraneous materials can enter the package during device assembly or even form particles. The package itself and assembly materials can be a source of contamination, especially in the form of gases and vapors. And if that weren't bad enough, the MEMS device can generate particulate during use, if there are any "wear" mechanisms where moving parts make contact. Although MEMS designers endeavor to reduce mechanical contact conditions where parts rub together or impact, this is not always possible. It is usually necessary to add stops to mechanical action areas for parts like mirrors or accelerometer combs where particles can be generated. The worst case for wear is designs with rotating gears or wheels on bushings or sliding mechanisms. Sandia has shown that wear particles will be generated and that parts may break even before contamination disables the system. But the package design can help solve all of these contamination problems, even particle generation, as will be seen later. Figure 3.3 shows MEMS wear out in a Sandia device that was specifically designed to evaluate wear and loose particle formation.

Many factors affect wear, including humidity, but any rubbing parts will generate particles that must be considered in package design and

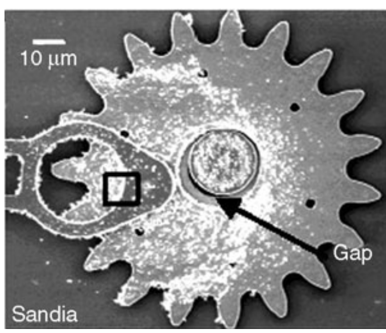


Figure 3.3 Wear and particle generation—Sandia.

environment control. Most commercial MEMS devices use torsion beams or some geometry that permits movement without contact. But even motion stops used in the DLP and other pivoting designs can make contact and break off particles.

3.2.4 Minimal stress

The cavity package eliminates stress on the top and all four sides of the chip that would otherwise occur, if the part were overmolded with encapsulant; a viable method with capped MEMS devices. Reduction of stress for cavity packages is an important added benefit, and can be the primary incentive for using cavity style packaging even when the MEMS mechanics is contained inside the chip or assembly, or protected by a cap over the active zone. But the MEMS device must be firmly secured to the package, typically by bonding the bottom of the chip to the floor of the package using solder or organic adhesive. Die attachment is accomplished with bonding material and this agent can be die-attach solder (usually gold-based), ceramic (glass frit), or polymer (die-attach adhesive). Polymer materials offer the lowest stress for thermomechanically mismatched chip-package systems, and can mechanically decouple the die from the package by absorbing stress during temperature cycling resulting from differential thermal expansion. Decoupling is valuable, if not critical, when there is a significant thermomechanical mismatch. This situation is also called *coefficient of thermal expansion* (CTE) mismatch, and it is a common problem since the package is often made of materials with higher expansion than silicon or other common MEMS device materials. Although not all MEMS devices are made of low-expansion silicon (CTE ~2.3 ppm/°C), we will assume that all devices will have lower expansion than the package.

The common die-attach adhesive is thermoset epoxy filled with silver to obtain thermal and electrical conductivity, although nonconductive

fillers, such as alumina, silica, and metal nitrides, are also used when electrical isolation is desired. Epoxies require fillers to reduce their own CTE value, which ranges from around 75 to 85 ppm/°C. But thermal conductivity is also desirable if the device generates heat that should be removed. That filled thermoset epoxy can be rather stiff will be indicated by a high modulus value; >10 GPa is high in terms of die adhesives and underfills. Epoxies can be flexibilized and die-attach adhesives are offered with modulus values well below 1 GPa. But flexibilizing epoxies can also increase outgassing due to less complete polymerization or use of nonreactive modifiers. Another approach is to use polymers with intrinsic elastomeric properties, which include silicones, some thermoplastics, urethanes, and a few others. Silicone die-attach adhesives are available with values as low as 0.005 GPa and are considered to be true "no-stress" products. Thermoplastic die-attach adhesives often have low modulus values and they do not build up stress during aging as can happen with epoxies that may slowly increase in cross-link density, especially at elevated temperatures. But thermoplastic die-attach adhesives must be heated to their softening point for bonding, and this temperature can range from 100 to over 300°C. Thermoplastic films can also require significant clamping pressure during bonding that may not be available in a die-attach machine used for epoxy thermosets. The amount of force that can be applied to a MEMS device may not be adequate for bonding. However, the thermoplastic class should still be kept under consideration unless ruled out by process considerations. Silicone die-attach adhesives are probably the first consideration when strain reduction is important. New products are now available that are intended for MEMS applications and most are designated as low stress or no-stress die-attach adhesives.

3.2.5 Temperature limitations

Several types of MEMS devices are temperature-limited and cannot tolerate the same temperature used in general electronics. Devices with significant limitations may require special packages that do not require the temperature extremes of solder assembly. The second-level interconnect can be mechanical, such as the "pin and plug" or "pin and socket" category. A *pin grid array* (PGA) or similar mechanical plug and socket second-level interconnect may be advisable. The PGA remains a popular package style, especially for CPUs where field replacement is important for repair or upgrade. A flex-based package can also be considered. A flying tail that emits from the chip can either be plugged into a connector or soldered without significant heat transfer to the device. It is possible to insert mold flexible circuits into plastic housing enclosures. Optionally, conductive adhesive assembly can be used where the process

temperature will be 150°C or even lower. The die-attach adhesive may also need to be selected for lower curing temperature. Chips that contain bioactive agents can be especially sensitive to heat and may even require storage at controlled temperatures prior to use. A PGA may be the best type of package here. Figure 3.4 shows ceramic PGA packages. It is also possible to design plug-in packages that will handle fluid and gas interconnects along with electrical.

3.2.6 In-package environmental control

Nonhermetic packages eventually come to equilibrium with the external atmosphere. Their in-package atmosphere cannot really be controlled except over a short-term interval. But hermetic and perhaps even near-hermetic packages can have an internal atmosphere that is regulated by in-package agents. Various getters and other atmosphere control agents are available and some are now used in MEMS and MOEMS packages. Getters are chemical scavengers that interact with specific molecules that would be expected to enter a package, be released by the package itself, or be formed by some reaction. Moisture getters are the most common type and have been used for electronic packages for decades and a few MEMS and MOEMS products for many years. Getters can be as simple as ceramic substrate that is predried before package sealing. Or they can be more complex like one of the hydrogen getters that adsorbs the gas, converts it to water by reaction with a compound, and then adsorbs the water with a moisture getter containing

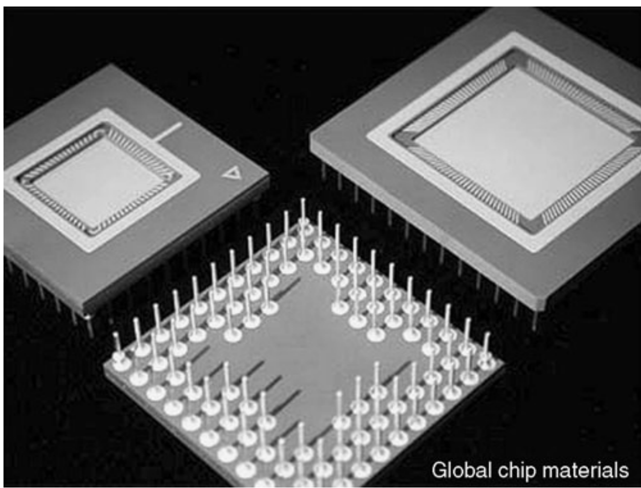


Figure 3.4 PGA package.

the same composite. Getters are not limited to gases and vapors. Particle getters can attract and hold onto tiny solids that break off from MEMS devices. They are sticky polymers that remain unchanged and do not outgas. Getter combinations can also be made up, and particle getters usually have moisture getter capability. See Chap. 5 for more details on atmosphere control agents.

3.2.7 Selective access to outside

One objective for electronic packaging has been to exclude everything possible from the outside environment. This is also a general goal for optoelectronic packaging and the solution has always been the fully hermetic package. Cost pressures and improved passivation have relaxed the “exclude everything” rule, but in no instance is the package purposely designed to allow gases and fluids from the outside world to enter and interact with the chip and its first-level interconnect structure. But the MEMS package does not always require total exclusion and the package may really be more of a mechanical platform than a protective enclosure. In fact, devices designed to analyze samples need access to these materials. A gas analyzer might require a package that allows the atmosphere to enter. But if the interest were only for a specific molecule, such as carbon monoxide (CO), then a selective membrane, or even a nanofilter might be possible. This is a new and relatively unexplored field and almost no literature is available. However, considerable separation technology is available from the fields of chemistry, biology, and physics.

Material sampling. MEMS devices or systems within a package may require materials that are not available from the environment and these must be supplied from reservoirs or sample containers. Ink jet printers are a good example. The MEMS jetting chip is connected to an ink reservoir or a group of three or more for color cartridges. We can expect to see a variety of MEMS jetting chips, pumps, sampling devices, reactors, synthesizers, body monitor/drug delivery products, and other innovations that have not yet been developed and announced. There will probably not be one universal concept here because of the variety of applications. Possibly, each package will be custom, although a family of basic types could eventually emerge. Some units might use a material that is contained within a package compartment or reservoir, just like the ink cartridge products. Others may require connections to equipment that will supply materials. And still others could have a sampling port that must be brought in contact with the material to be analyzed. A blood analyzer, for example, could have a small opening or even a capillary tube for introducing material to the chip. More complex devices,

such as chemical or drug synthesizers, could have several input reservoirs and output containers, all on a microscale crafted using MEMS fabrication methods. MEMS drug delivery chips that will use noninvasive methods for both monitoring and delivery are in development and under study. It will also be possible to build packages that can interconnect electrical power, signals, and materials. Figure 3.5 shows such a concept with interconnecting chips.

Force sensing. MEMS pressure sensors may still need protection from water and other materials that can cause corrosion and contamination. The simplest solution is to add a flexible barrier with either hermetic properties or a material that is hydrophobic.

3.2.8 Mechanical shock limits

MEMS devices can be shock sensitive though they are made from very strong materials. The stiction phenomenon where two surfaces become locked together and are held strongly by atomic forces is just one phenomenon that limits the ability to withstand mechanical shock. Stiction is covered in the next section in more detail, but let it suffice to say that it resembles the bonding seen when two clean microscope slides are pressed together. Regardless of the need to limit shock, the package can reduce the forces transmitted to the device. Plastic packaging probably offers the best shock absorption and energy dissipation. The die-attach adhesive can also absorb energy. But for the most part, shock sensitivity will be dictated by the device design, although antistiction agents can help.

While stiction is bad, adding mechanical energy absorbing structures may not be a good idea either. MEMS devices that measure inertial change or analyze vibrations may require good transmission of mechanical force. Accelerometers intended for air bags may be desensitized by energy-absorbing systems. So, before deciding on mechanical force altering designs, make sure that everything is taken into account.

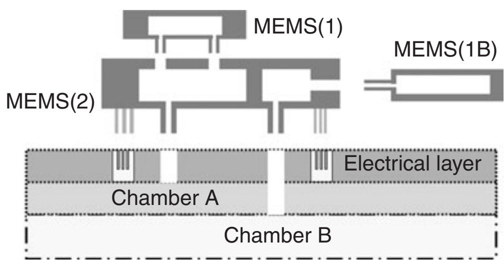


Figure 3.5 Interconnecting MEMS chips.

Active mechanical characteristic of MEMS makes the packaging and assembly process much more complex.

3.2.9 Stiction

Stiction, or *static friction*, is the sticking or locking together of relatively smooth surfaces that come in contact. Short-range attractive forces exist between any surfaces that make contact, but MEMS problems are exacerbated because of the small size. When devices are made smaller, the ratio of surface area to mass increases. At some point the surface area is high enough and the mass is sufficiently low that parts coming in contact are held together with a force that is greater than the MEMS actuator force attempting to move them apart. They become permanently stuck when there is insufficient force in the "MEMS motor" to get things moving. This force can be a million times higher than the actuation forces available within the chip. Stiction can also occur in disk drives and cause a hard crash, as the head becomes attached to the spinning disk instead of floating above it. MEMS sensors are being used to monitor drives and keep them out of such failure zone modes.

Since stiction occurs when surfaces come together, MEMS designers do everything possible to prevent contact. Even though the MEMS actuator may not cause surface contact by design, a mechanical shock can bring parts together, thus creating stiction. Stiction increases with moisture content as confirmed by work at Sandia National Laboratories. Sandia has studied both stiction and wear. But while stiction decreases with moisture reduction, wear increases as humidity drops. In the case of stiction, water molecules act like an adhesive (hydrogen bonding), but like a lubricant for moving surfaces in contact with one another. When the MEMS design requires contact between moving parts, usually a construction to be avoided, the solution for antistiction and antiwear seems to be the addition of hydrophobic lubricants.

Antistiction agents can be added to the package interior. One of the earliest materials was a silicone fluid; a drop of fluid was added, the package was briefly heated to vaporize the liquid, and the lid was finally sealed. Other solutions include thin liquid coatings of lubricants and thin solid coatings. Texas Instruments uses a fluorinated fatty acid, *self-assembled monolayer* (SAM) on the aluminum oxide surface in their *digital micromirror device* (DMD). Silicones and fluoropolymers are the most commonly mentioned additives. Solid polymer films, like parylene have also been suggested. There are now several parylene compounds including a fluorinated product originally designed as a low-k dielectric. The fluorinated material, called Nova HT, has high thermal stability, low k, low surface tension, and is optically clear. Antistiction agents and other additives are presented in more detail in Chap. 5.

3.2.10 RF shielding

Some devices require shielding to prevent *electromagnetic interference* (EMI) or *radio frequency interference* (RFI). When there is an EMI/RFI issue, shielding must be applied to all packaging materials that are not electrically conductive. Only metal packages are self-shielding. In some cases, a metal lid can be used on a ceramic or plastic and this will suffice. Plastic and ceramic packages can be plated with metal by well-known methods such as electroless nickel plating. Once a “seed coat” of metal has been applied, electrolytic plating can be used to build thickness or to apply a different metal such as copper. When nickel is used, the surface can be protected with an inexpensive gold flash called *immersion coating*. Immersion gold is a type of electroless plating that is self-limiting and selective. Gold ions replace nickel metal atoms and convert them to nickel ions in this redox reaction. This double displacement reaction stops when no more nickel is available. Figure 3.6 shows molded plastic caps that have been plated with electroless nickel, followed by electrolytic nickel and then immersion gold.

3.2.11 Fluidics management

A number of MEMS fluidic devices have been developed and they include pumps, valves, and even reactors with interconnecting channels between chambers. Most are still lab systems for the most part, but we can expect to see a host of products in the near future. Connections have been made through external manual microplumbing, suggestive of a Rube Goldberg style. Figure 3.5, shown earlier, depicts the general concept of directly connected MEMS devices and auxiliary components such as reservoirs. Commercial systems will need packages that can quickly enable fluid connections. We can also use models from the macroworld.

Figure 3.6 Metal-plated packaging caps.

Quick-connect hardware has been developed over many decades for both gases and fluids, in both research and industrial environments. Air and gas connection methods can serve as models for equivalent microsystems. We should consider similar designs on a smaller scale, and there is no reason why MEMS fabrication cannot produce and utilize quick-connect-disconnect fittings.

Some MEMS fluidic coupling research work has appeared in the literature and the feasibility of incorporating fluidic fittings into MEMS devices has been affirmed. MEMS fabrication methods can produce *three-dimensional* (3D) structures like the ones needed for couplings. Ellis Meng of California Institute of Technology and Paul Galambos of Sandia are just two researchers who have published valuable papers on MEMS fluidic coupling research. There is already some *intellectual property* (IP) in the area that is bound to increase. Fluidic interconnect technology will be valuable for pumps that will have an inlet and outlet for connections to other components like reservoirs and holding containers. The technology is well suited to chemical and biomedical analyzers. MEMS devices to be connected will have ports and even pipe extensions that are complimentary to those on the pumps and other connectable devices. The connection ports can be readily fabricated from silicon and perhaps coated with a polymer such as parylene to enable remarkable connections. These concepts can be somewhat similar to laboratory glass wear that can be assembled to build the desired system. Interconnecting pipes and fittings could be made with MEMS 3D fabrication capability to produce complimentary pin and socket structures that could carry materials as shown in Fig. 3.7.

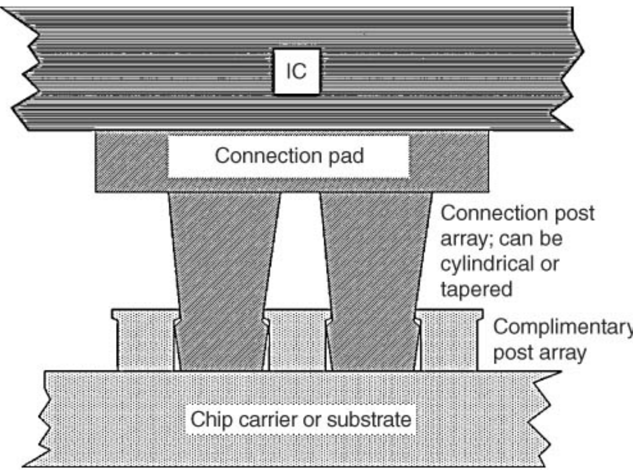


Figure 3.7 Interconnect structures.

3.2.12 High-vacuum enclosures

A few MEMS devices require a high vacuum since air molecules will impede motion. These are typically high-speed *radio frequency* (RF) chips that operate at very high speeds. Even the presence of inert gases is a problem since these molecules reduce the oscillation rate of the moving part. Perhaps metal packages are the best consideration here because of a long history in high-performance fully hermetic systems.

3.2.13 Device as the package

Some MEMS structures do not require protection from the environment. Energy devices such as MEMS rockets or turbines will not need to be encapsulated although they will eventually be incorporated into a system. The device itself is the housing. Some may argue that rockets and turbines are not really MEMS devices but miniature engines. The electrical I/O feature is missing and energy is supplied as chemical fuel. While it may be a stretch to fit microrockets and gas turbines into our MEMS definitions, related concepts such as turboelectric generators could qualify. Regardless, there will be some MEMS devices that don't need enclosures. Perhaps the ink jet chip comes closest for a commercial product. The chip is robust enough to not require protection, except for the electrical interface that is usually covered with polymer. The MEMS chip itself is exposed and can actually be touched by the end user.

3.2.14 Cost

The package fabrication process often has the greatest impact on final cost. The materials used generally limit the processes that can be employed. The level of hermeticity required has tended to dictate the materials. Package hermeticity level is therefore equated to the cost range. This equation may change with innovations in materials and also by developing methods of combining materials in cost-effective ways that perform like the more expensive single component types. But it is also imperative to determine what level of hermeticity is actually required. Machined metal packages are at one extreme end of the cost spectrum and are not a serious consideration for anything but highly specialized MEMS chips, or perhaps complete systems. Metal cans should be considered since their cost is much lower, although their size and shape may limit use as will be seen in the section that describes them in more detail. Ceramic hermetic packages are lower in cost than a typical metal type and many more designs are available as will be seen in the section describing them. Ceramic packages continue to be used for MEMS devices and some of the newer configurations, like the *quad flat no lead package* (QFN), are even less expensive. Today, the ceramic

QFN and similar packages are the starting point for MEMS inertial sensors where no I/O except electrical is required. However, plastic packages are still significantly lower in cost. Plastic packages, especially injection molded types, can be made more complex without adding cost. It is possible to add ports for gases or fluids by simply designing them into the mold instead of adding individual parts, as is typically required with metal and ceramic packages.

3.3 Hermeticity; Levels, Evaluation Methods, and Requirements; Perceived versus Actual

Some developers have tried to define hermeticity on just the basis of the fine leak test method, but this is a misapplication of the test and an incomplete definition. The helium fine leak test, true to its name, is designed to test for leaks. It is not intended to measure barrier properties of packaging materials. The test is typically applied to metal-hermetic packages to ensure that the lid and pass-through points for conductors do not have leaks as the result of faulty processing. Since solid metal is a near-perfect barrier to gases, any helium that passes through a metal package is due to one or more leaks at an interface point. Plastic cavity packages made from high-performance plastics, such as LCP type resin, can generally pass the fine leak test but this only indicates that the lid seal or metal conductor interface is secure. Passing the fine leak test should not be interpreted to mean that the package is hermetic, nor that the seal is hermetic. The detection limits of this test method may seem extraordinary but the test is not sensitive enough to measure very low transmission rates of helium passing through the package walls or lid. There is no doubt that oxygen and water vapor pass through all plastics that are not coated with some type of barrier material such as metal. Helium balloons once had a lifetime of only a day or two as the gas leaked out of the plastic enclosure. Balloons today are typically coated with very thin metal film to boost their lifetime up to many weeks.

The MIL-STD-883 METHOD 1014.11 Test Method Standard, Microcircuits[1] is titled, “Seal” with the objective, “The purpose of this test is to determine the effectiveness (hermeticity) of the seal of microelectronic and semiconductor devices with designed internal cavities.” The test defines leak rate as the quantity of dry air at 25°C in atmospheric cubic centimeters (cc) per second, flowing through a leak or multiple leak paths from a high-pressure side of one atmosphere (760 mmHg absolute) to the low-pressure side at or less than 1 mmHg absolute. Standard leak rates are expressed in units of atmosphere as cubic centimeters per second ($atm \cdot cm^3/s$). The method can detect leaks down to about 10^{-9} $atm \cdot cm^3/s$. Apparatus required shall consist of suitable pressure

and vacuum chambers and a mass spectrometer-type leak detector preset and properly calibrated for a helium leak rate sensitivity sufficient to read measured helium leak rates of 10^{-9} atm · cm^3/s and greater. The volume of the chamber used for leak rate measurement should be held to the practical minimum, since this chamber volume has an adverse effect on sensitivity limits. Failure criteria: "Unless otherwise specified, devices shall be rejected if the measured leak rate (R_1) exceeds $1 \times 5 \times 10^{-8}$ atm · cm^3/s."

So what is the right criterion for hermeticity? Since moisture can have a critical effect on some MEMS and MOEMS devices, this would seem like the most important single test area. MIL-STD-883 METHOD 1004.7 MOISTURE RESISTANCE, Test Method Standard, Microcircuits, is a reasonable starting point for evaluating package moisture resistance. The stated purpose of the procedure is as follows:

"The moisture resistance test is performed for the purpose of evaluating, in an accelerated manner, the resistance of component parts and constituent materials to the deteriorative effects of the high-humidity and heat conditions typical of tropical environments. Most tropical degradation results directly or indirectly from absorption of moisture vapor and films by vulnerable insulating materials, and from surface wetting of metals and insulation. These phenomena produce many types of deterioration, including corrosion of metals; constituents of materials; and detrimental changes in electrical properties. This test differs from the steady-state humidity test and derives its added effectiveness in its employment of temperature cycling, which provides alternate periods of condensation and drying essential to the development of the corrosion processes and, in addition, produces a "breathing" action of moisture into partially sealed containers. Increased effectiveness is also obtained by use of a higher temperature, which intensifies the effects of humidity. The test includes a low-temperature subcycle that acts as an accelerant to reveal otherwise indiscernible evidences of deterioration since stresses caused by freezing moisture tend to widen cracks and fissures. As a result, the deterioration can be detected by the measurement of electrical characteristics (including such tests as voltage breakdown and insulation resistance) or by performance of a test for sealing. Provision is made for the application of a polarizing voltage across insulation to investigate the possibility of electrolysis, which can promote eventual dielectric breakdown. This test also provides for electrical loading of certain components, if desired, in order to determine the resistance of current-carrying components, especially fine wires and contacts, to electrochemical corrosion. Results obtained with this test are reproducible and have been confirmed by investigations of field failures. This test has proved reliable for indicating those parts that are unsuited for tropical field use."

The test sets the pass limit at 10,000 ppm or 1 percent relative humidity (RH) after the package has been exposed to accelerated conditioning; 85 percent RH/85°C. Some will feel that this is an extreme condition, especially if the package will only experience much milder conditions. Many variants of the test have evolved with lower temperatures and lower humidity values. But measurement of in-package humidity remains the valid criterion. We have run this type of test on plastic packages that have easily passed the helium fine leak test but no plastic came even close to maintaining a low in-package moisture value. The procedure and results will be reported in Sec. 3.6.6.

3.4 Cost versus Performance Trade-offs

The electronics industry, the largest in the world, owes its astounding success to the integration of transistors marked by the invention of the integrated circuit nearly a decade after the transistor was demonstrated. But developments and innovations in the electronic component package area should also receive tribute for their role in enabling low-cost consumer electronics. The successful implementation of the plastic nonhermetic package enables high-volume electronics to proceed since cost targets can be achieved. Packaging continues to drop in cost as progress continues in both design and manufacturing. The advent of wafer-level packaging will continue to drive down cost that now averages well under 5 percent of the total component, and newer packages are reducing the package value to about 3 percent of the total cost. But this low total percentage of cost has only been true for nonhermetic plastic packaging. There are many other ways to reduce costs through packaging, since the processes, not the materials, are the key issue. The key is to understand processes and how they are affected by design.

3.5 Emergence of Low-Cost Near-Hermetic Packaging

In the year 2000, the idea of a low-cost near-hermetic package (NHP) for MEMS began to take form after discussions at the NSF-sponsored workshop.[2] But while a desire to reduce cost is noble, the task is complicated by many considerations. As we have discussed in earlier sections and in other chapters, packaging has many functions and even more requirements for MEMS.

3.5.1 Definition and description

A hermetic package must pass the helium fine leak test and exclude environmental contaminants, especially moisture for a long period of time.[3]

This also means that contaminants, if present, must be reduced to an acceptable level before sealing. The definition for NHP is still being determined, although "good enough and cheap enough" is the goal. The NHP should be good enough to satisfy the requirements for many, but not necessarily all MEMS devices. But MEMS packages are going to be product specific in many if not most cases. Furthermore, product categories will also determine some of the requirements. For example, the package for an airbag sensor would be expected to take more abuse and have a longer lifetime rating than a package for a game motion sensor. So for now, we will set aside the desire for a precise and quantitative definition. In terms of cost, it may be possible to put an absolute value on some packages since some MEMS producers are setting cost targets for new packages before they will even be considered. We could also set interim cost targets as a percentage of the total system, but this could be difficult since MEMS fabricators are driving down cost of some of the high-volume products like inertial and pressure sensors. We could also try setting target on cost per pin (I/O), but this may not be realistic because of the low count for many of the MEMS devices. Absolute cost targets by end-use application may be the best way to start and also to gauge progress.

3.5.2 Material choices

Choices for package enclosure materials seem wide-ranging until we narrow the list based on their physical, chemical, electrical, and mechanical properties, comparing them to the specific requirements for a device and application. For example, a capped MEMS accelerometer might perform satisfactorily in a simple overmolded plastic nonhermetic package since the MEMS mechanical parts would be shielded from direct contact with encapsulant by the cap. But if encapsulant-induced stress became an issue, then a cavity style package would be considered next. Stress would be minimized and the hermeticity requirement could be minimal, if the cap and seal were hermetic. But if the MEMS device was uncapped, a cavity style package would be needed and the hermetic performance would be more important. A plastic cavity package would be suitable for the capped MEMS, but testing would determine how well the uncapped version would perform. But, if the device were an optical-MEMS type, any moisture ingress could be much more critical and a fully hermetic package could be required. It may be noted that several of the early MOEMS DLP packages from Texas Instruments were not hermetic, since the glass lid was sealed with epoxy adhesive and later with UV-cured materials that are probably inferior to LCP in terms of barrier properties. A high moisture barrier plastic, such as the LCP class of resins should be able to meet all of the device requirements, with

the possible exception of hermeticity. This material would produce a near-hermetic enclosure, but that might not be good enough for optics. But could a hermetic barrier coating be added to the plastic? There are a number of barrier coatings that have been reported to improve hermeticity of plastics, and such a "composite" would be a candidate for higher performance plastic packages; for more on barrier coatings see Sec. 3.5.5.

3.5.3 Interconnect schemes

Producing the enclosure is perhaps the easiest task for packaging since we have so many choices, but adding the electrical interconnect is the bigger challenge depending on the enclosure material. The interconnect has always been metal or a metal-filled composite. This could change in the future as advancements are made in carbon-based nanomaterials, but for now, the selection must come from metals. *Metal lead frames* (MLF) and various patterned conductor arrays on dielectric substrates have been used and remain popular today. The MLF can be stamped or etched from steel, nickel, kovar, nickel-iron alloys, copper alloys, and other specialty alloys. Stamping produces lower quality edges and tooling can be expensive, but it is the low-cost winner for high volume applications. Substrates include organic rigid circuit board types used for area array such as BGAs, ceramic with cermet conductors used for flip chips and multichip modules, and thin flexible circuitry materials that are used in *tape-automated bonding* (TAB), *chip scale packages* (CSP), and newer stacked packages. The conductor structure has been challenged by high-density needs from electronics where the number of I/Os increases each year, but this is not a present concern for MEMS with its relatively low interconnect requirements. The more critical area for conductors MEMS in packaging is probably materials compatibility. The metal must be compatible with the enclosure especially when a high level of hermeticity is needed. This means that a good bond and seal must be created between the conductors and the pass-through regions of the enclosure.

3.6 Manufacturing Process Comparisons

3.6.1 Metal packages

Metal packages are almost always a sealed enclosure type that is classified as fully hermetic. The cavity can be formed by machining a billet or block of metal using traditional metal shop procedures like milling, drilling, and grinding. These classical methods are time-consuming and require high skill levels, but they produce precise custom parts with almost no tooling. This method is ideal for prototyping but is used for

production, especially for optoelectronic modules, and military RF modules in limited volume. The relatively higher cost makes it a less desirable process for MEMS. Material manufacture and packaging fabrication are two separate processing steps: (1) the fabrication of the material in a billet or sheet and (2) machining of the billet into the desired shape. For all but the simplest shapes, the cost associated with packages fabricated in this manner are associated with the machining to the desired geometry and the billet stock, most of which is lost to machining. Often these packages require additional assembly operations to add functional components such as seal rings, feed-through ports, and substrates that add to the total packaging cost.

Metal injection molding (MIM), also called *powder injection molding* (PIM), is also being applied to manufacturing electronics parts. MIM can produce 3D solid metal parts, including cavities, and is the metal analog to plastic injection molding. MIM is capable of producing an almost limitless array of highly complex geometries in many different alloys ranging from stainless steels, alloy steels, and soft magnetic materials, controlled expansion materials (low CTE), and custom alloys. MIM is presently used to manufacture moderate- to high-volume products including electronic heat sinks, hermetic packages, electrical connector hardware, and fiber optic connectors. Tooling costs can be expensive and this process is more suitable for high volume, although single cavity molds can be used for prototypes and lower volume runs. Feedstock is first compounded from fine metal powders ($<25\ \mu m$) and polymer binder. The feedstock that will be used in the MIM process uses specific binder and metal powder formulations that can be pure metals, alloyed powders, or mixtures of metals. Standard plastic injection molding machines and tools are used to produce MIM parts. Since the polymer binder is present in the feedstock, mold cavities are designed approximately 20 percent larger than the final part size. Like plastics, MIM molds may have multiple cavities, inserts, slides, unscrewing cores, and hot runner systems. After molding, green parts are sintered at temperatures up to 1400°C, so that the polymer binder breaks down and dissipates while the metal particles retain all of the molded features. The metal particles fuse together during sintering and the part shrinks approximately 20 percent to form a solid metal part.

Metal forming has been used to make everything from aluminum beer cans to TO type packages and it is a good high-volume automated process that is viable for MEMS packaging considerations. Metal is shaped by drawing, extruding, forging, coining, super-plastic forming, and other processes that produce 3D-shaped metal parts. Forging can produce complex free-form geometry in metals. The forging process reduces the amount of material waste and therefore lowers material costs. Forging also improves production speed and gives a more favorable

grain orientation in the finished part so that higher strength is often achieved. In forging, the workpiece is compressed between two dies. The piece is often heated in order to temporarily reduce strength and increase ductility during the deformation. Due to the large forces the dies are relatively expensive. Super plastic forming is an alternative to conventional forging and drawing of sheet metal. Tooling costs are much lower but processing times are longer and measured in hours. Only the concave half die is needed. The metal plate is fixed to the die, heated, and moderate air pressure is added. Slowly, over a couple of hours the plate will be pressed into the die by the air pressure. Only special types of super-plastic metals can be used—aluminum, titanium, and stainless steel.

Casting can also be used, but vacuum and pressure casting are now preferred instead of the atmospheric casting. Pressure casting is essentially the MIM process. However, no plastic sacrificial binder is used, but rather composites like *aluminum silicon carbide* (AlSiC) that can be made into preforms by compounding silicon carbide with aluminum. This is really a ceramic material that is covered in more detail in that category.

Overall, metal packaging seems like the least suitable option for MEMS packaging, but there is another very simple type of metal-hermetic package process to consider that was mentioned earlier. The metal can style package, shown in Fig. 3.8, has been around longer than any other and was originally used for transistors. The TO is still widely used for transistors and lasers. Metal can packages consist of a metal base with leads exiting through a glass seal. This glass seal can be a compression seal. After device assembly in the package, a metal lid (or can) is resistance welded to the metal base forming the hermetic seal. Metal can style packages usually have a low lead count, less than 24 leads, but this is suitable for many of today's MEMS products. Best of all, cost is low. These packages should be considered for some MEMS applications that do not require anything but electrical I/Os, perhaps even RF-MEMS. Figure 3.7 shows a higher lead count version with details of the construction.

3.6.2 Ceramic packages

There are a variety of schemes for producing ceramic packages suitable for MEMS. The two common processes are (1) laminated ceramic, using the cofired method that is useful for multilayer conductors, and (2) the pressed ceramic method. The laminated ceramic process employs unfired "green" alumina or other ceramic precursor composition tape that can be cut via holes fabricated, and patterned with conductors before firing at high temperatures into a hard ceramic package platform. The individual

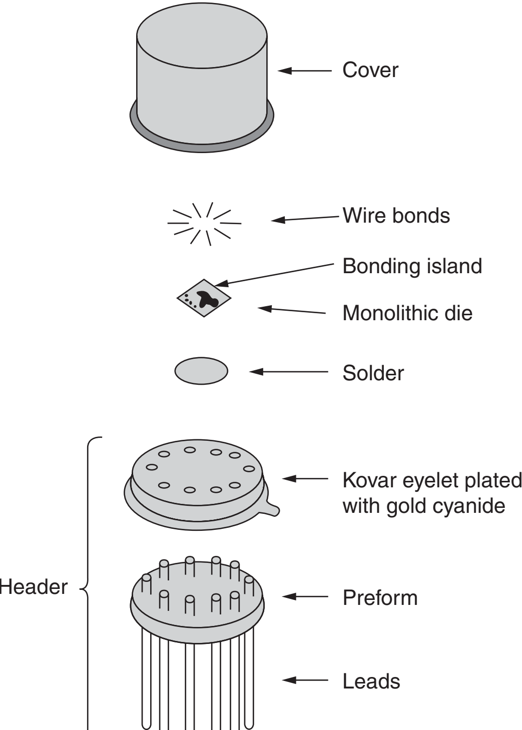


Figure 3.8 Metal can package—exploded view.

layers can be aligned to one another, and then fired as one, or cofired, into a single interconnected structure. Cofired ceramic technology refers to the process of combining multiple layers of cast ceramic tapes that have been printed with cermet conductive ink patterns and printed-through vias, stacking them together so the metallized layers connect through the vias, and firing (sintering) all of them together in a furnace to create a monolithic body. The most commonly used material is alumina that has been blended with other ceramic compounds, glass powder, organic binders, solvents, and plasticizers. The additives, considered proprietary, provide control with a predictable shrinkage rate and good adhesion of all layers. More recently, low or no shrinkage types have been introduced that have lower firing temperatures and are designated as *low-temperature cofired ceramic* (LTCC) systems. The metallization merges together to create connections from the pad on the chip to a lead, pad, or pin through vias. Many variants for the process exist.

The pressed ceramic process was first developed by IBM in 1963 and was called s*olid logic technology* (SLT). It used a sandwich made up of a pressed ceramic body and a lead frame connected with borosilicate glass. Following the chip assembly, a ceramic lid with glass preform is used to seal the cavity. This process was initially used for creating ceramic *dual in-line packages* (DIP) with up to 64 pins, and subsequently extended to chip carriers, which are either leaded or leadless. The pressed ceramic package is usually a three part construction: base, lid, and leadframe. The base and lid are manufactured in the same manner by pressing ceramic powder into the desired shape and then firing. Glass is then screened onto the base and lid, and then fired. During package assembly, a separate leadframe is embedded into the base glass. The hermetic seal is then formed by melting the lid glass over the base and leadframe combination. This seal method is referred to as a frit seal, and therefore this package is often called a glass frit seal package. The pressed ceramic packages are typically lower in cost than are the multilayer type packages, since the process can be fully automated. See Fig. 3.9.

Research continues in the metallizing and metal composite areas with much directed toward packaging. *Metal matrix composites* (MMCs) are materials composed of metal and ceramics in varying ratios. Materials such as AlSiC appear to have properties that can provide a promising packaging solution especially for thermal problems. Within the past ten years AlSiC material(s) and components have provided packaging solutions with required thermal management performance, improved and new functionalities, and at a competitive cost compared to traditional packages.[4] This material is manufactured by infiltrating molten aluminum into porous-shaped AlSiC particulate preform to produce parts such as heat spreaders,

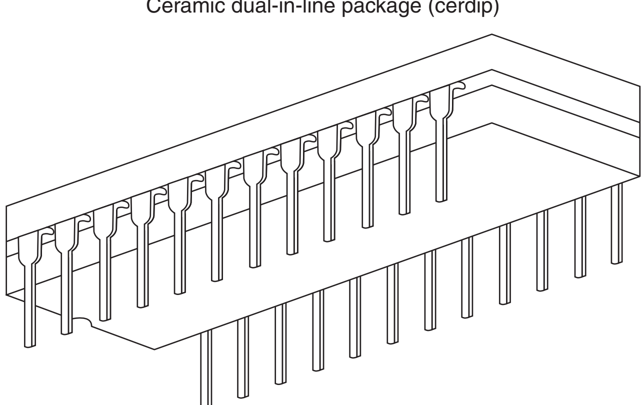


Figure 3.9 Ceramic DIP or cerdip.

microwave housings, and base plates. AlSiC could offer significant advantage for the electronic packages including low CTE (6 to 7 ppm/K) and low density (0.9 to 3.0 g/cm^3) making it about one-third the weight of Cu. The thermal conductivity is approximately 150 to 180 W/m · K. However, its mechanical strength is twice that of Cu. The material could be used in a squeeze-casting process.

A commercial process called QuickSet/QuickCast is an AlSiC fabrication process that consists of first fabricating a porous SiC particulate preform using a molding process. The preform has the exact geometrical features of the final housing with dimensional tolerances held typically to +/–0.001 in (0.025 mm). The SiC particulates are uniformly distributed in the preform which, when infiltrated, results in a uniform composite microstructure. The SiC particulate concentration is also controlled by the injection molding process, and is held to +/–0.5 vol%. By controlling the preform solids concentration the Al/SiC ratio of the final housing is controlled to maintain a reproducible CTE behavior.[5] The SiC preforms are assembled into inexpensive and reusable infiltration mold tooling. Functional components can also be assembled in this tooling with the SiC preform for concurrent integration. The infiltration tooling has the exact dimensions and tolerances of the final product. Using pressure assistance, molten Al-metal (typical casting alloys) are forced into the pore structure of the SiC preform to form a dense hermetic composite material in the desired product shape geometry.

Ceramic packages are certainly useful for MEMS and MOEMS and are currently popular although most users complain that the cost is too high. Ceramics provide low mass, can be mass produced, and can have a relatively low cost compared to metal. They can be made hermetic rather easily, and if hermeticity is essential, they are probably the best choice. Multilayer ceramic packages could also allow reduction in system size and overall cost by integrating multiple MEMS and other components into a single hermetic package. But several problems can affect the reliability of the cofired-type package. First, the green-state ceramic shrinks during the firing step, although LTCC appears to be resolving this issue. There can also be an issue with ceramic-to-metal adhesion that is not as high as ceramic-to-ceramic adhesion. Warping has been an issue, but can be reduced or eliminated by reducing the differential shrinkage rate of the metal and ceramic. The ideal system will be matched and the metal will not react chemically with the ceramic during the firing process. But this limits the selection; metals most frequently used are tungsten (W) and molybdenum (Mo). The LTCC class of packages is the state of the art ceramic to consider for MEMS package needs, when a fully hermetic system is required. The LTCC conductors can be Ag, AgPd, Au, and AuPt. Ag migration has been reported to occur at high temperatures, high humidity, and along faults in the ceramic of LTCC, but may not be an issue for many MEMS applications. However, if

fluids, especially any that contain water, will come in contact with the package conductors, then metal electromigration should be checked.

Currently, most open-die MEMS accelerometers are packaged in a surface-mount ceramic package that costs approximately $0.50 for an eight-lead device. Overall, ceramic packaging (including custom assembly operations) amounts to half of the manufacturing cost of a complete sensor. While ceramic packaging reduces cost over most metal packages, plastics can reduce cost even further. But is their performance adequate? Next, we'll look at plastic packaging.

3.6.3 Plastic packages: plastic versus ceramic

Ceramics are superior in many respects to plastics and possess a combination of electrical, thermal, mechanical, and dimensional stability properties unmatched by any other group of materials. Ceramic substrates can provide the highest wiring density of all substrate technologies, but only if multilayer constructions are used. Organic-based flexible circuitry is capable of extremely fine lines (~1 μm) when additive patterning is used and produces the highest density package for single- and double-sided circuits. *Plastic encapsulated microelectronics* (PEMs), the ubiquitous nonhermetic package, offer many advantages over hermetic packages in the areas of size, weight, performance, availability, and cost. Therefore, it's not surprising that plastics account for more than 97 percent of the worldwide commercial packaging market. Commercial PEMs generally weigh about half as much as ceramic packages (for example, a 14-pin plastic DIP weighs 1 g against 2 g for the 14-pin ceramic DIP). *Smaller outline packages* (SOPs) and thinner configurations, such as *thin small-outline packages* (TSOPs), are available only in plastic. Plastics have better dielectric properties than ceramics and the dielectric constant can be well below 3. *Plastic quad flat pack* (PQFP), pin-grid arrays, and ball grid arrays (PBGA) are favored for minimizing propagation delays. Newer flex-based CSPs and multichip packages have made considerable gains in recent years. However, at very high frequencies (up to 20 GHz) better and more predictable performance is obtained with ceramic packages. Ceramic packages almost always have a higher material and testing cost, and are fabricated with more labor-intensive manual processes. PEM based on thermoset epoxies and transfer molding does not readily lend itself to cavity style packaging. However, more recent thermoplastic packaging using injection molding, is well suited for producing cavities. Both of these plastic packaging systems are now being used for selected MEMS applications. We must note that capped MEMS or devices without exposed moving parts are required for overmolded packaging. Capping, however, will be considered part of packaging and not device fabrication even though it is a wafer-level process.

Capped MEMS chips. MEMS chips can be capped at wafer-level before moving to full packaging. The capping process can provide hermeticity and prevent contamination and damage during sawing and packaging. Capped MEMS chips are usually suitable for plastic packaging, since full hermeticity is no longer required for the enclosure and polymer encapsulant can come in contact with the chip. Stress from the encapsulant remains an issue that may require evaluation. The important factor is protecting the delicate micromechanical structures from being stained by the injected plastic; lower-shrinkage *epoxy molding compound* (EMC) could make the difference. A gel cap over the microstructure before transfer or injection molding could reduce stress. Wafer-to-wafer bonding capping techniques have gained wide acceptance in the MEMS industry and now are being used by most MEMS inertial sensor manufacturers, including Analog Devices, Motorola, Delphi, Sensonor, and STMicroelectronics.

Wafer-on-wafer capping has some disadvantages, however: (1) The anchor region where the cap seals to the sensor die must be at least 200 μm wide all around the micromechanical structure to ensure a hermetic seal, and that translates into a significant increase in chip size and chip cost. (2) Wafer-on-wafer capping yields dies that are 200 to 500 μm taller (i.e., thicker) than standard IC dies so the wafer-capped device cannot be packaged as is in a standard 1.5-mm-tall surface-mount *small-outline plastic* (SOP) package. The wafer stack can be lapped down, or an extra tall plastic package mold can be used, but again at extra cost. (3) Wafer-to-wafer bonding requires very flat and clean wafer surfaces, so any surface contamination or excessive surface roughness can result in a nonhermetic seal and yield loss. (4) Overmolding can cause unacceptable stress on the capped chip. Future caps will be thinner and more precise. Several new processes are in development.

Analog Devices, Inc. (ADI) is one of the early developers of capping and has reported on the process in detail. Figure 3.10 shows the last steps in the process and the result after overmolding. The capping ADI process, like most of the others, begins with fabrication of the capping wafer that is typically silicon. The wafer is etched to create precut sections that will allow wafer singulation by sawing from the top. The wafer is bonded by first applying glass frit paste, drying, and then aligning the wafer cap to the MEMS wafer. Low-temperature firing (<500°C) fuses the two wafers together. The assembly is ready for sawing and the delicate MEMS mechanisms are protected from contamination, and has an important benefit of capping. The cap is now singulated by precision partial sawing as shown in Fig. 3.10. Note that the saw blade must be aligned to intersect with the edge cut. The caps are now singulated and the wafer is now cleaned. For all purposes, it is a "live" wafer ready to be sent out for packaging. The MEMS active section is protected, but the bond pads are

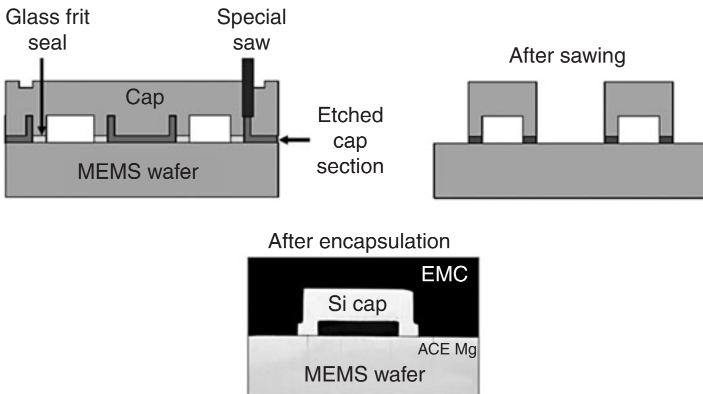


Figure 3.10 Capping process.

exposed and available for wire bonding. The packaging foundry can now dice the wafer, attach the die, wire bond, and overmold, since the cap prevents the encapsulant from contacting the active motion section of the chip. But note that there are many steps to capping and that the chips must still go through an entire final packaging process. Also note that the epoxy encapsulant surrounds the cap and chip to transfer any stress from shrinkage to the MEMS device. Capping technology appears to be very well covered by countless patents even though many researchers continue to work and report on the concept as if it were novel.[6–12]

While the idea of placing a cap over a device at wafer level may not be that new, there are innovative variations on the theme. The biggest problem with capping is the double singulation requirement. A single sawing operation would be much easier and more cost-effective, but the chip pads must be available for connection to the package. One solution is to cap with a structure that will route the pads to the top of the cap, as shown in Fig. 3.11. The cap would need to provide an interconnect array that matches the layout of the MEMS bonding pads. Conductive vias would be required to convey the signal from MEMS pad to the cap

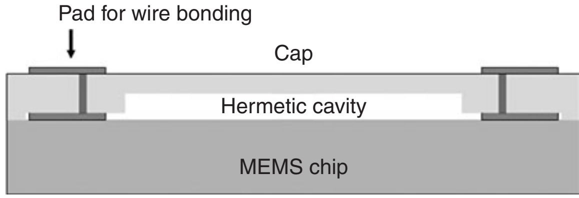


Figure 3.11 Cap with interconnect.

pad, and this could be done with existing technology. And finally, the pads on the cap would need to be wire bondable, but this again is well-known technology. The wafer bonding could also be accomplished by well-known methods and the result would be a hermetic seal. Only one singulation step would be required instead of the two now used commercially. The singulated chip would now be packaged in the usual way since the chips would be fully protected. Wire bonding would be straightforward since there is no cap in the way.

We can take the concept a step further and add bumps, pins, or some other second-level interconnect system to the cap. The result would be a finished package with no need for further processing or encapsulation. The interface could be a solder bump created at wafer-level or a pin array produced by MEMS fabrication methods. The cap-package base could be made from a transparent material, although silicon is transparent to some of the infrared spectrum. This could be used for MOEMS or OE chips. The light path would be directed at the PCB or module that could have light piping built in, something that is already being done. These concepts are all shown in Fig. 3.12 as a self-contained fully hermetic chip-size package.

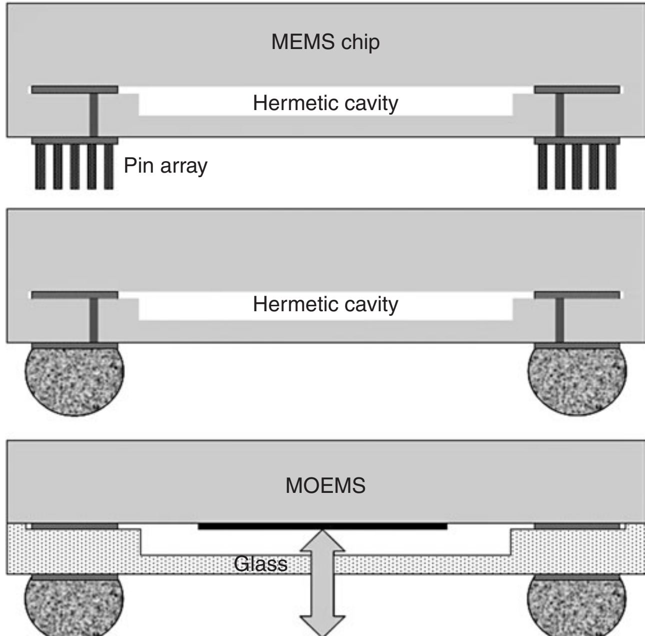


Figure 3.12 Package caps with second-level connections.

Post-molded plastic packages. The transfer molding process has been used for about 50 years to encapsulate electronics and remains the most popular packaging process today. The resulting product is PEMs, more commonly known as the plastic package. The steps are straightforward: a chip is attached to a lead frame that is normally a strip or an array of chip-bonding sites. Polymer adhesive is the common die-attach material and it is usually dispensed at the wire bond station. Once the adhesive is rapidly hardened using heat, the wire bonds are made from the chip pads to the corresponding lead frame bond sites. The entire "loaded" array or strip is placed into the mold cavity. The transfer mold consists of a heated chamber that is separated from the cavities, but connected to each through a system of runners and gates. The process begins by closing the mold. Simultaneously, prepolymer, typically EMC in the form of solid preheated preform (called a puck), is placed into the chamber and heated. An auxiliary ram then pushes the melted material through the runner and gates into the cavities, completing the transfer process and forming the molded part.

The process has many advantages–loading a preform into the pot takes less time than loading preforms into each mold cavity; tool maintenance is generally low although gates and runners are susceptible to normal wear; longer core pins can be used and can be supported on both ends allowing smaller diameters, because the mold is closed before the process begins; delicate inserts and sections can be molded; and tight dimensional tolerances perpendicular to the parting line are possible. If the mold is properly designed and operated, flash is extremely thin and easy to remove, higher tensile and flexural strengths are easier to obtain with transfer molding, and automatic degating of the mold's tunnel gates provide cosmetic advantages. Some of the concerns are: molded parts may contain knit lines in back of pins and inserts, the cull and runner system of transfer molding leaves waste material, and compared to compression molding, high molding pressures are required for the transfer process, so fewer cavities can be put into a press of the same tonnage. Figure 3.13 shows a lead frame before die bonding, Fig. 3.14 shows EMC ready to be automatically placed into the heating chamber or pot, and Fig. 3.15 depicts the transfer molding process.

EMC has been advanced continuously since its first application as an encapsulation material for semiconductors. The purity has been improved substantially in order to prevent device failures caused by ionic contamination. Formulations have been modified to achieve a higher reactivity for shorter processing times and a higher equipment output. In addition, filler shape and distribution were fine-tuned to achieve high filler contents and subsequently low thermal expansion coefficients. At the same time, optimizing the distribution of the filler's particle size helped to improve the compound's flow behavior even in today's thin wall packages.

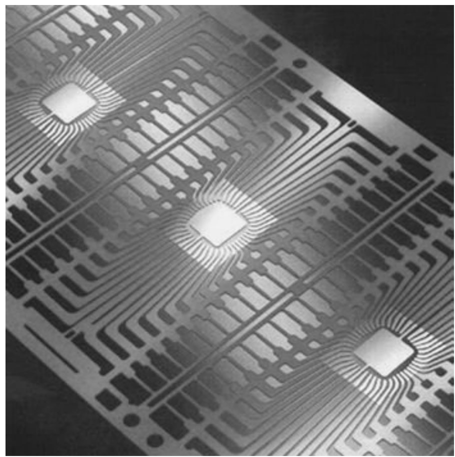


Figure 3.13 Metal leaf frame (MLF).

Adhesion of the compound to the leadframe and the device has been improved to avoid internal delamination and the so-called “popcorn” effect (explosion of packages caused by the formation of steam from absorbed moisture during heating in vapor phase soldering). However, EMC is still a somewhat mediocre material from the view of moisture absorption and barrier properties.

Figure 3.14 EMC preform; pucks. (*Source: Cookson Electronics Semiconductor Products.*)

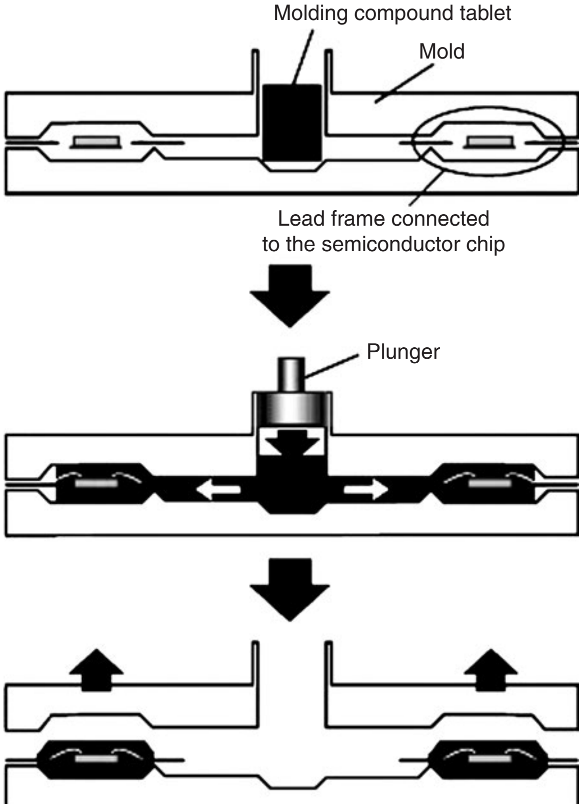


Figure 3.15 Transfer molding.

Premolded. Premolded packages can be made by both transfer and injection molding. By definition, the premolded package is made first and then the device is added in a sequence similar to the one used with metal and ceramic cavity packages. The transfer molding process can form cavity enclosures by designing the appropriate mold, but this is not a very common process. *Plastic injection molding* (PIM), however, is very well-suited to 3D cavity style and several companies now offer molded cavity packages made from high-temperature plastics such as *liquid crystal polymer* (LCP) or *polyphenylene sulfide* (PPS). Today's thermoplastics, the other major class of polymers, are now superior to EMCs in the most critical packaging categories. Engineering plastics can take the thermal abuse of lead-free soldering, have an order of magnitude better moisture resistance, are rapidly shaped into precise 3D structures, and some can pass flammability standards without adding halogens, phosphorus, nitrogen compounds, or hydrates. The thermoplastic-shaping processes have also

kept pace. *Injection molding* (IM) can produce tens of thousands of packages in an hour—all automatically. Micromolding has advanced to a level where precision parts can only be identified under a microscope and dimensions are approaching 0.1 μm. There is nothing that will prevent IM from moving into the nanoscale range, and highly touted nanoimprinting shares some of the same attributes. One of the most valuable features of IM is that it can readily produce complex 3D cavity style package structures while incorporating prefabricated conductor structures. IM can be scaled up, to form strips or arrays of cavity packages at high volume and low cost, using economical engineering plastics like LCP. The LCP thermoplastic materials class has been in commercial use for more than a decade but has recently been popularized as a new flexible circuitry substrate.

The IM process first fluidizes the plastic resin with heat and mechanical energy, injects it into a closed metal mold that can have 100 or more package-shaped cavities, and then finally ejects finished parts after the mold opens; the cycle is repeated. A complete IM cycle for MEMS packages takes about 10 s. The hot molten plastic is quickly cooled by the mold to form a tough solid part that will not melt during soldering. IM, one of the most pervasive manufacturing processes, is used around the world to produce large and small parts for every industry, including automotive and electronics (mostly housings and mechanical parts). One drawback, however, is that large multicavity molds can be expensive.

The simplest molded packages employ a *metal lead frame* (MLF) for the interconnect that is stamped out as a strip or an array. The MLF is placed into an injection mold similar to the way it would be positioned into a transfer mold. But the MLF is not loaded with chips, and the mold is designed to create cavities instead of flooding plastic over the entire chip and frame. The mold is closed under very high clamping pressure that is measured in tons; press ratings are often in clamping force. Next, the injector ram forces molten plastic into the mold cavities under fairly high pressure. LCP has a very low viscosity in the molten state, making it ideal for precision molding. The mold is usually cooled (may still be above ambient) using a water jacket connected to a chiller that removes heat and recalculates water or a heat-transfer fluid. The molten plastic solidifies in a few seconds, the mold opens and ejector pins push parts out of the mold. The process repeats itself and is usually automated. Figure 3.16 shows the insert molding process.

Several thermoplastic MLF packages have been designed by QLP, a start-up company that is focused on thermoplastic cavity packages for MEMS and other niche applications. They are now producing packages for capped MEMS gyroscopes that are too stress-sensitive for overmolding. For assembly, the MEMS device is adhesively attached to the package floor followed by gold wire bonding. Silicone gel may be added

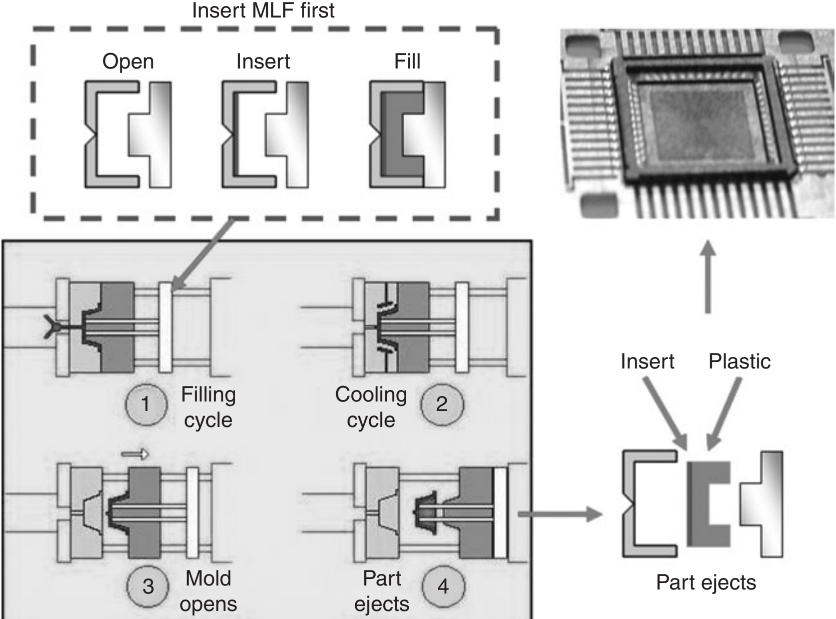


Figure 3.16 Insert molding process.

over the wire bonds to ensure that there will be no corrosion. A molded plastic lid is finally attached by direct heat application or ultrasonic bonding. Figure 3.17 shows one of the package designs for MEMS.

Einstein cautioned that “Everything should be made as simple as possible but not simpler.”[13] Perhaps the great mathematician was being

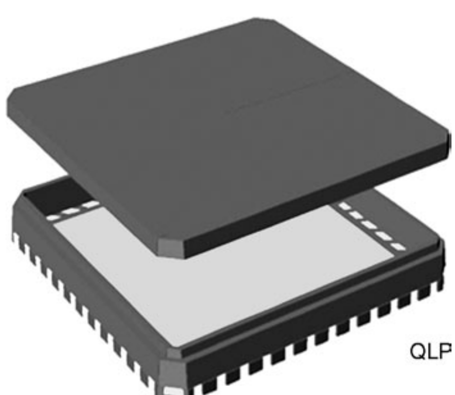


Figure 3.17 QLP package.

facetious, but maybe he was being profound. While the phrase is not really a mathematical statement, it can be turned into an axiom, *Always seek the lowest common denominator for a design*, and applied to packaging. Simplicity should win when low cost is important. Once a design is reduced to the simplest form, it cannot be reduced any further since oversimplification would construct a false premise and that's what Einstein could have meant when he said, "but not simpler."

Most electronics is not much more than electrical insulators and conductors, but in just the right arrangement. The package is an electrically insulated platform and usually an enclosure with electrical conductors. As discussed earlier, the MLF can be overmolded with thermosets, or insert-molded with thermoplastics. But the MLF is actually not the lowest common denominator, since there are simpler ways of running connectors through the package. The MLF is first punched or etched from metal coil that generates cost and waste. After molding, the MLF (now embedded in the package) is cut out of the strip or array generating more cost and waste. The simplest way to make a durable and precise package is to insert-mold—the simplest form of conductors using IM. Since the mold can have hundreds of cavities, the process can produce hundreds of premolded packages every 10 s, all automatically. There is no real waste from plastic runners that bring resin to the mold, as it is simply returned to the molding machine as regrind-recycled resin. There is only MLF waste, but a new design can eliminate it. The vital requirement for reusable plastic is that the material be remeltable—a thermoplastic, not a thermoset. Thermoset scrap is not easily reused and is often disposed of as hazardous waste. Epoxy can be classified as hazardous because it typically contains halogens. Incinerating halogen-containing waste can form toxic materials similar to the notorious "Agent Orange." Epoxy developers may be removing bromine, but replacing it with other flame retardants like red phosphorus. Phosphorus is probably a bad choice because this element can combine with other waste, especially in a flame, to produce physiological agents. Toxic phosgene and many nerve gases contain phosphorus. There are other flame retardant agents and special resins, but they add cost and compromise performance in many cases. This is the right time to consider alternatives to epoxies and the thermoset class!

Fortunately, some of the thermoplastics that are ideal for packaging (high temperature, low moisture) also pass V-0. This may seem fortuitous, but the same molecular orientation that produces good gas barrier properties also reduce flammability. Many prefer the LCP where polymer chains align into orderly crystalline structures even in the liquid state, hence the name. These carbon, hydrogen, and oxygen based molecules are superb environmental materials having the same elemental makeup as many foods. Most LCPs have intrinsic flame retardancy

without additives. Fillers such as glass are used to modify properties, however. LCPs have been used for a long time to make precision, moisture-resistant parts like optical fiber connectors, and there is a wealth of knowledge here.

Commercial LCPs have about 10 times better gas barrier performance than epoxies and behave more like glass when it comes to moisture but are still not hermetic. This is the right moment in time and technology, and environmental awareness, to move packaging to thermoplastics and solve some of the MEMS packaging issues, especially cost. The infrastructure is in place, but not within the packaging area. There are many more injection molding machines than transfer molding presses. Although the packaging industry has not found much value in thermoplastics, MEMS can be well served by these materials. Injection molding is ideal for making cavities and the value of the process will increase as more complex packaging is needed for advanced MEMS, especially fluidics and biomedical products.

Assuming that LCP is an optimum polymer packaging material and that injection molding is the ideal shaping process for cavity style packages, the next consideration is the design. One goal is to define the simplest electrical through-package interconnection scheme beyond the MLF. While technically viable, organic circuit substrate (area array—BGA) is too expensive, substrate is the most expensive part of the BGA and a source of moisture-related problems. One can, and should, also consider an insert-molded leadframe made with flex circuitry. While useful for more complex package interconnects, flex does not meet the simplicity criterion. The simplest "lead frame" is a set of discrete or unattached connectors. They could be pins and plastic PGAs that are made with pins, but this would not be the simplest and the most economical unless the package needed to have a remakable second-level connection.

The most natural and universal shape in nature is the sphere and therefore one of the easiest and cheapest to manufacture. Natural attractive forces at both atomic- and macrolevels readily form spheres. Molten metal and gigantic suns form spheres, unless other forces distort the shape. Industry manufactures hundreds of spherical products ranging from solder powder to silica filler. Spheres are easy to handle since they are symmetrical. Metal choices are limited. Solder must be rejected since it would melt at the molding temperature of more than 300°C. The spheres must be made of nonfusible metal such as copper or nickel. Both are available as spheres and both can be soldered although each is optimized with a suitable finish. Nickel can be plated with gold, silver, or palladium. Copper could be first plated with nickel and then finished with metals just mentioned. Nickel is a paramagnetic metal and this feature could be used for picking and placing spheres into the mold.

But copper is well-suited, available as spheres, and more malleable. Billions of metal spheres are used in ballpoint pens and all kinds of other applications making them a low-cost commodity. A reasonable starting point for the spheres is 30 mils and a package thickness of about one-third to permit the sphere to protrude through the bottom and into the cavity. The metal ball becomes the equivalent of the pin for a PGA, but the sphere is cheaper and better suited for molding and soldering.

After sphere insert-molding, the resulting electrical interconnect structure is a lead frame that is held in a pattern by the plastic. The ball layout is determined by the molding tool that will have tiny curved depressions, or dimples, to accommodate and hold the metal balls. The lead frame inventory becomes a container of metal spheres in standard sizes. The mold design will determine the number and position of the balls, and one might even use mold inserts to program and change the I/O pattern. The metal balls can be automatically placed into mold cavities using a vacuum pickup, a concept similar to the BGA solder ball placers. The entire package could be manufactured automatically in a molding machine with a "ball placer." Figure 3.18 shows the ball insert-molding concept.

Ball insert molded with thermoplastic resin appears to be the simplest and lowest cost process for manufacturing cavity packages that are potentially suitable for MEMS devices. Any change like using metal cylinders instead of spheres makes the system more complex and more expensive. There is no routing with this design, although one could be added by insert molding a flex circuit, or by selectively plating, and could be an approach for high I/O chips. But if we want to keep it simple, the ball-to-chip link can be done with wire bond if the balls have the right finish. Palladium over nickel is a reasonable choice and has been used on lead frames for decades by Motorola and others. The palladium is very suitable for wire bonding and does not degrade solder as can occur with gold. The Ni or Pd finish is lead-free and compatible with lead-free solders. One more benefit is that Pd tends to be readily wet by polymers to adhere tightly. The packages can be molded in a multiple array of

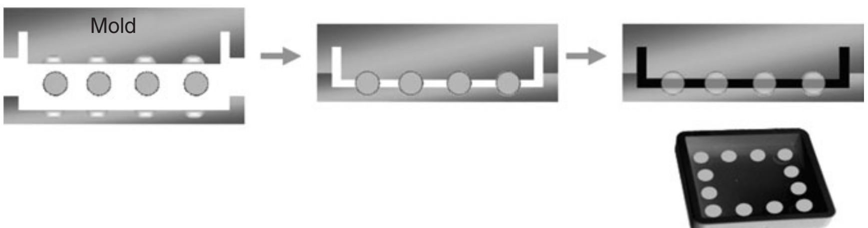


Figure 3.18 Insert ball molding process.

several dozen or even hundred parts for efficient handling. Small connection tabs can hold parts together until chip assembly and testing. The packages can then be singulated by punching, cutting, lasing, or snapping the tabs. Testing can be carried out while packages are still in array since the ball conductors are isolated. Conventional lead frames must be excised or singulated. But a multicavity mold would require modest to high volume production.

Chip assembly is similar to the process used for any other package. The package array moves to die attach and wire bonding that can be done on a conventional line. The package array can be molded in a layout to fit the same footprints as conventional package substrate strips. Once chips are assembled, the lids can be bonded to enclose the package. This can be done with individual lids or with a sheet of suitable material. Glass lids can be used for optical devices, including MOEMS, but plastic is preferred for MEMS. LCP can be used, as well as other plastics including optically clear types. The lid sealing can be accomplished with any number of bonding methods including adhesives, thermosonic, and laser welding. The sealed packages can be tested and singulated. Lidding can be a sheet and this can serve as a carrier for test and burn-in. Since the balls are made of Cu or Ni, they can be socketed for test or burn-in without deformation that can occur with solder balls. The singulated plastic NHP is now ready for standard SMT assembly. Solder paste is applied to the *printed wiring board* (PWB) by stenciling without any additional steps since paste is needed for the other SMDs anyway.

Prototyping of an insert-molded ball package. Matrix, Inc. (East Providence, RI) designed a prototype mold with a two-up (two identical cavities) with an array of 16 concave depressions in the base, and top mold to accommodate the 16 metal balls. The package was designed to accommodate a commercial 16 I/O MEMS gyroscope. Balls plated with palladium over nickel were placed in the mold depressions with a vacuum pickup. Once balls are loaded, the mold halves are closed and LCP resin is injected. The mold quickly cools the resin. The mold is opened and an ejector pushes out the parts. The cycle is repeated. High-volume production would utilize a mold with multiple cavities and the parts would be held together in a standard array by small tabs. Figure 3.19 shows parts made with the prototype mold.

One concern was wire bonding to a curved surface that is the top surface of the ball that protrudes into the package. Experts disagreed on the advisability of bonding to nonplanar surface. A mold could be designed so that the ball-capture depressions were shallow or even eliminated on the package floor side. This would not add cost to the process and could even reduce cost of tooling. Embedded balls could be coined

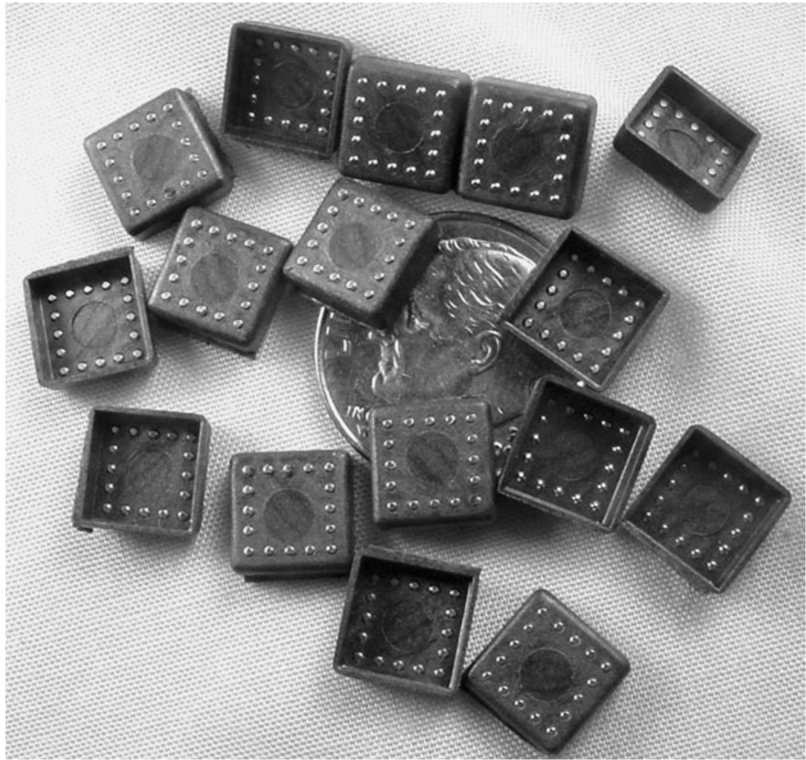


Figure 3.19 Insert-molded ball package.

after molding and this would produce a compression fit. Only the upside, or wire bond side, requires coining and this was accomplished using a microarbor press. Tests confirmed that the coined balls could be wire bonded and the plating remained intact. Figure 3.20 shows a package with coined balls suitable for wire bonding.

3.6.4 Chip assembly in plastic packages

Chip assembly in plastic cavity packages is no different than for metal or ceramic cavity packages, and the same die attach and bonding wire materials can be used. The chip is attached with adhesive that is thermally cured. Gold wire bonds are made after the adhesive is hardened.

3.6.5 Lid sealing

Once the MEMS chip is attached and wire bonded, the package can be sealed. The lid can be made from almost any conductor or nonconductor:

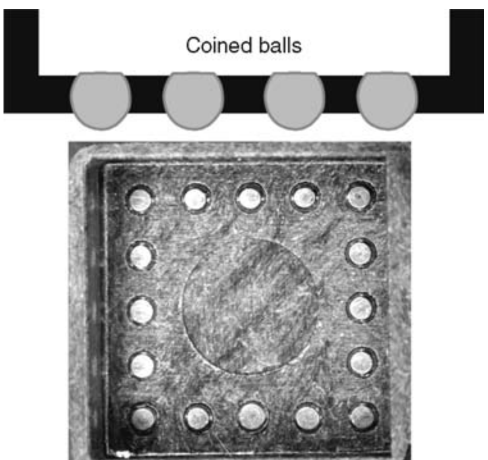


Figure 3.20 Package with coined balls.

metal, ceramic, glass, or plastic. Although adhesive will work, we evaluated sealing using a Speedline Technologies prototype laser. The unit had an adjustable power 30 W near infrared unit that uses a Coherent, Inc. diode array source with a wavelength of about 802 nm. The unit has programmable X-Y positioning tables. A literature search showed that the idea of using lasers for sealing plastic-to-plastic goes back to the 1960s when lasers were first being explored for industrial use. Packaging literature indicated that the concept of using a laser to seal glass lids to LCP injection-molded packages was a known public domain art, free of patent restraints. A Kodak patent describes an LCP package for CCD where the glass lid can be bonded "cover glass 16 would be attached to the top open area of ring frame 14 by any of numerous conventional means including but not limited to: adhesive; heat sealing; ultrasonic welding; or laser welding."[14] The inventor did not claim laser sealing to LCP packaging, but rather disclosed it as being known. Others also reference the use of laser energy through glass as a lid seal method. Laser lid sealing, while not a standard packaging process for plastics, appears to have merit for MEMS and MOEMS, where adhesives could be a source of contamination.

Glass seals well to LCP provided that the plastic housing absorbs laser energy. Fortuitously, most commercial plastics absorb some infrared. Even if the plastic is transparent to *infrared* (IR) and *near infrared* (NIR), carbon black filler that is commonly compounded into molding resins is an excellent absorber. Both EMCs and many plastics are typically colored black with dispersed carbon as the standard color. Clear resins can be obtained and colorless IR absorbers are available from ClearWeld, but packaging is typically black, in part, to prevent light transmission that can interact with ICs. The glass seals passed both the gross leak test and helium fine

leak test. The fine leak test was performed by an outside lab that reported no detectable leaks for 25 samples within the limit of their test sensitivity of 1×10^{-9} atm·cm^3/s He. Once again, passing the helium fine leak test is *not a* proof of hermeticity or ability to pass MIL STD testing.

Trials were also run on LCP film and sheet material tested as a lid seal. The lid material should have no IR absorber so that heating will occur at the interface. This process is referred to as *transmission welding* and is well known. Lid thickness for testing ranged from 2 mils to about 25 mils. While a 2-mil-thick film is readily bonded to the LCD package, the material is probably too thin. There is no need to use thin, biaxial-oriented film that is much more expensive than molded materials. The maximum thickness limit was about 25 mils for this laser, and scattering appeared to reduce the beam energy to a level where sealing was marginal. Figure 3.21 shows the laser sealing equipment.

3.6.6 Package barrier issues

Unfortunately, no plastic is a perfect barrier to small molecules, especially oxygen and water. These polar molecules can travel along the polymer changes by well-known mechanisms including hydrogen bonding.

Figure 3.21 Speedline Technologies near-IR laser.

Epoxies are known to absorb moisture and that becomes a problem during soldering when explosive vaporization causes damage to the package. This is known as *popcorning*. While some thermoplastics have much better moisture absorption properties, they are never hermetic as was shown by experiments to be described next. But it should be possible to add hydrophobic agents to the resin or apply a barrier coating to the finished package that would improve barrier properties.

Barrier coatings that may provide hermeticity are theoretically possible and work has been reported. The simplest high-barrier coating is metal, but a design would be needed where the metal barrier did not short out the electrical conductors. Metal can readily be applied to plastics by vacuum coating or plating, so the application will not be an issue if a concept can be developed to prevent short out. Nonconductive barrier coatings have been developed and this approach may be more fruitful; shorting would not be a concern. One example of a barrier coating that could be viable is the Schott PI-Coating that uses plasma-impulse-chemical-vapor-deposition and is said to form hermetic barriers on plastic. A plastic package would be placed in a chamber that is evacuated and then flooded with a gaseous coating precursor. Microwaves would be the source of energy for the plasma that decomposes the gaseous precursor. SiO_2 could be deposited on the outer surface of the package or the interior. The pulsing of the plasma can be repeated to provide the required thickness required for a good barrier. The plasma process is noted for producing homogenous coatings. One issue is that the barrier material would need to be selectively applied to avoid insulating the metal conductors. Alternatively, coating would need to be removed from conductors adding cost. Economics could be an issue even if full hermeticity was achieved on plastic packaging.

3.6.7 Hermeticity testing of injection molded packages

The first step before testing the moisture barrier properties of plastic was to review resin properties to ensure selection of the best material. Table 3.1 shows key properties of high-temperature injection molding

TABLE 3.1 High-Temperature Injection Molding Plastics

Plastic	Water abs. (%)	Melting point (°C)	UL94	CTE/30% glass
LCP	0.02–0.10	280–352	V-0	0–18 ppm
PEEK	0.15	340	V-0	16 ppm
PPA	0.15–0.29	310–332	H-B V-0	22–40 ppm
PPS	0.01–0.04	280	V-0	19–27 ppm

LCP = Liquid Crystal Polymer; PEEK = Polyetheretherketone; PPA = Polyphthalamide; PPS = Polyphenylene Sulfide

plastics from the final candidates considered for packaging. Today, there are some very good thermoplastics for electronics applications. The first criterion is high-temperature stability—being able to survive the soldering process for lead-free solders. The LCP class was selected for the excellent properties shown in the table and for low cost and commercial availability of many grades; different fillers and loadings. While there are dozens of thermoplastics that might meet general packaging criterion, the LCP class is now the plastic of choice with a softening point of around 300°C. This material, produced by large resin makers, has a long history of use in such areas as fiber optic connectors. While fiber optic connectors do not necessarily need high-temperature performance, dimensional stability is high on the list. LCP's low moisture absorption equates to excellent dimensional stability because of low hygroscopic expansion; most materials expand as their moisture content increases (hygroscopic coefficient of expansion). So a low moisture absorber, like LCP, will show small growth under high humidity. But low moisture absorption is also valuable for electronics, and for even more reasons (like no popcorning).

As mentioned earlier, injection molding does generate nonproduct pieces as runners, but, unlike epoxies, the material has value and can be sold or simply reused. Any waste LCP can be reground and reused, or sold. Thermoplastics can be remelted since they do not "set." This also means that in a future that may be closer than we realize, electronic product reuse/recycling will be easier. The thermoplastics can be separated from other classes of materials by the process in use today for general recycling now employed in most municipalities. The plastics industry is very large and ubiquitous. Plastic injection molding equipment is found all over the world. Industrial cities can have a dozen or more injection molding companies with dozens or hundreds of machines. So there is no problem with infrastructure when viewed from the outsourcing perspective. Table 3.2 shows LCP film properties compared to typical polyimide films used for flexible circuits. Table 3.3 gives moisture transmission characteristics.

Although passing the relatively easy helium leak test is desirable, and is probably a first requirement, this should not be touted as proof of hermeticity or even verification of a hermetic seal when polymers make up the bond layer. All plastics allow moisture to pass through, and LCP is no exception. Water vapor transmission is the most important criterion since water serves as a catalyst and medium for numerous undesirable reactions within a package. Moisture penetration is the most common failure mode of microdevices used in high humidity or liquid environments.[15] We therefore decided to measure the internal relative humidity using a *temperature and humidity* (T&H) sensor from Sensirion. Table 3.4 also shows results of exposing sealed LCP caps to 85 percent RH/85°C.

TABLE 3.2 LCP Flex Data from 3M Co.

Property	PI 1	PI 2	LCP	Test
Tensile strength (kpsi)	50	42	15	D882, 64T
Elongation (%)	60	40	15	D882, 64T
Young's modulus (kpsi)	800	825	700	D882, 64T
Tear strength (g)	26.2	17.5	15.4	D1922-00A
Heat shrinkage % at 200°C	.08	0.04	0.04	D2732
CTE (ppm/°C)	13	14	18	D696, 44
Moisture absorption (%)	2.4	2.0	0.1	D570, 63
CHE (ppm/%RH)	9	8	2	D570
Moisture trans, rate (gm/sq/cm/day)	4.2	3.8	0.4	F1249
Dielectric constant	3.3	3.1	3.0	D150
Dissipation factor	.005	.005	.003	D149

LCP is 2-mil commerical film from 3M Co.; PI 1 and 2 are commerical polyimide films.

While connections through glass would have been more desirable, project fund limits only allowed a connection through the cap that could add more entry points for moisture. However, the smallest holes were used and the wires were sealed with silicone encapsulants in a best effort with low funds. Table 3.4 shows the T&H curve measured inside the package while exposing to 85 percent RH/85°C, while Fig. 3.22 provides the humidity versus time values for the experiment. Figure 3.23 shows the sensor and connection through the LCP test cap before lid sealing.

3.6.8 Package enhancement

The package can be provided with special features to enhance performance of the enclosed device as required. They include thermal dissipation, mechanical shock resistance, increased access sensitivity to environment (e.g., pressure sensor), and others. The package can provide several enhancements if required by the specific device and application. One of the more common is thermal enhancement. A heat spreader, conduit or heat sink is typically incorporated into the package. This can be

TABLE 3.3 Water Vapor Transmission of LCP—Auburn

Sample ID	WVTR ($g/m^2 \cdot day$)	Permeability ($g^3 mil/m^2/day$)	Diffusivity (cm^2/s)	Solubility (g/cm^3)
2L (2 mil)	0.1177	0.2354	$2.589 \times 10e^{-9}$	0.000268
2H (2 mil)	0.1373	0.2746	$2.838 \times 10e^{-9}$	0.000284
4L (4 mil)	0.0678	0.2712	$9.830 \times 10e^{-10}$	0.000811

SOURCE: Auburn University.

TABLE 3.4 In-Package Humidity Testing

Sample N	Joining speed (mils/s)	LCP film thickness (mils)	Gross leak test	Starting conditions		Condition at the end of exposed time	
				% RH	Temp (°C)	% RH	Temp (°C)
L 9	30	5	Pass	13	28	66	85
L 10	30	5	Pass	16	25	69	85
L 11	30	5	Pass	16	25	72	82
L 12	30	5	Pass	17	21	56	87
L 13	40	5	Pass				
L 14	20	10	Pass				
L 15	30	5	Pass				
L 16	20	10	Pass				

Exposed time at 85°C/85% RH is 168 h.

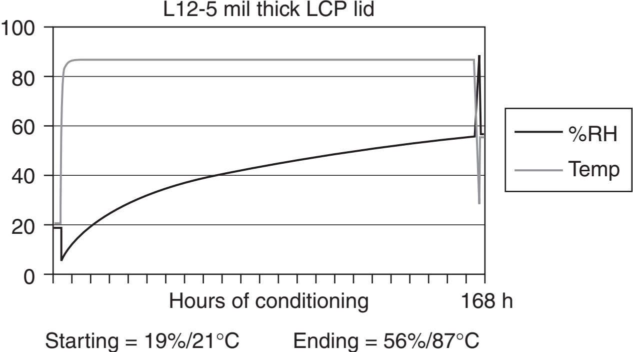


Figure 3.22 T&H inside of package curves.

part of the lead frame or a separate metal insert that is added in the same process where the conductors are introduced. While most MEMS devices are not expected to generate significant waste heat, some like the Texas Instruments DLP, may be exposed to heat that needs to be managed.

3.6.9 Productivity using strips and arrays

Molded packages can be made in a multiple array format for increased productivity, throughput, and economics as suggested earlier. This is now a standard concept for overmolded packages. A lead frame is generally fabricated as a strip or array that fits into the corresponding

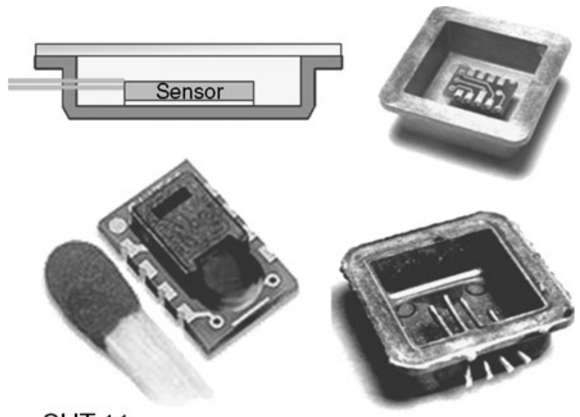


Figure 3.23 In-package T&H sensor.

array of mold cavities or an open or flood mold, with no cavities. The number of parts in an array may be in the hundreds for productivity and efficient handling. Packages can be singulated after molding by cutting or excising individual package leads. While individual mold cavities were the most common, flood molding or area molding has become popular for BGAs and similar area array packages. The encapsulant is molded over the entire array of chip carriers so that one single plastic body is produced. The encapsulant is sawn to singulate the packages. This method has better economics and lower tooling cost. Injection-molded packages might also be molded in an array. Individual packages can be interconnected with small tabs that hold everything together for chip-attach, but can easily be cut after the package is completed.

3.6.10 Acceptance of NHP molded package technology

New packaging concepts, designs, materials, and processes have been more easily accepted in the past decade because of the intense development in this area, and the need to quickly adapt to change. Many will argue that packaging has been too quick to accept new designs and that this has resulted in an overload—too many packages—and this is probably true. However, with MEMS, the devices and their requirements are fundamentally different, making it imperative to accept the best solution even if this requires new processes and equipment. With that said, the packaging industry has a history of hanging onto old concepts longer than necessary. This was seen when with the SMT revolution where new SMT packages did not take full advantage of the technology benefits and many manufacturers simply bent leads of old package designs to obtain SMT compatibility. It took a while for packaging to move to new, small footprint designs that took real advantage of the SMT processes. This same inertia was seen with the area array package revolution, where many stayed with perimeter designs to a point where an excessive number of overly thin leads made assembly almost impossible. But this may not be the case with MEMS packaging. Some of the large packaging foundries have adopted new package processes including injection molding. But the small start-ups are leading the charge to true MEMS-specific packaging.

3.6.11 Status of NHP and MEMS-specific packaging

Companies like Silicon Bandwidth, California, tackled plastic molded packages to solve needs in optoelectronics and they were one of the first to mold packages with LCP. Unfortunately, their timing was unforeseeably bad for serving the optoelectronic market that was about to implode;

the result of the telecom bubble-bursting phenomenon a few years ago. While SI developed valuable packaging concepts, they were not able to pursue MEMS to any degree. RJR Polymers, another small California-based company, also worked with molded packaging and they continue to offer products, but seemed to have focused on optoelectronics. Their general design uses insert-molded metal lead frames and LCP molding, and they could offer MEMS packages. More recently, Massachusetts start-up QLP began working on LCP molded packages for MEMS and other cavity applications. They offer a variety of MLF LCP plastic packages and some target MEMS. They are reported to be producing LCP molded packages for the analog devices gyroscope using a QFN style cavity package and are said to be expanding production capacity.

3.7 The Packaging MOEMS (Optical-MEMS)—Additional Requirements

MOEMS, or optical-MEMS, has most of the same requirements as nonoptical MEMS in terms of connectivity, freespace, no contamination, and atmosphere control, but an optical pathway must be added. Most also believe that optical systems require a higher level of hermeticity since the optical path must remain clear and optical parts and devices can be moisture sensitive. The Texas Instruments DLP micromirror light controller can be viewed as the reference standard by which to judge other MOEMS packages. Today, the DLP uses a fully hermetic ceramic cavity package, though much work has been done on polymer materials. There may not be a better option for this demanding product although early products used nonhermetic packages, since the glass was sealed with thermal epoxy and then UV-cured adhesive. One of the special requirements, and one that is very demanding, is the ability to tolerate high-intensity lighting that has a significant infrared component. Projector light sources, especially for large cinemas, cause significant heating that may exceed the limits of the best plastic candidates. But there are many other MOEMS devices that have less severe requirements.

3.7.1 Windows and ports

The earliest MOEMS commercial product appears to be the Airline Ticket Printer from Texas Instruments launched around 1992. The optical print head for the *airline ticket boarding* (ATB) used a MOEMS device with 840 mirrors (2×420) in a rectangular chip (0.64 in $\times$ 0.18 in). The original package had a glass window that was thermally bonded to the ceramic header with B-staged epoxy that was later changed to UV-cured adhesive as a manufacturing improvement step. This nonhermetic package was later changed to a fully hermetic type using laser metal-glass fusion bonding. Texas Instruments tried a number of glass

sealing strategies including, indium compression seals, gaskets, soldering via laser reflow, isolated reflow, and amalgams. These approaches were apparently unsuccessful due to loss of hermetic integrity during environmental testing and other failures.

The modern DLP and other light controllers for special projection use glass windows for the light entry and exit portal. Many other devices, such as spectrophotomers and infrared imagers, also require a window. These windows may have special coatings, such as filtering and *antireflective* (AR) that make glass the best choice. Although most are not MEMS devices, some digital camera packages, especially those for mobile phones, use nonhermetic packages made of organic materials. Many of the simple optoelectronic devices in the light emitter class use a wide range of packages including some molded from plastic. LEDs take advantage of plastic to reduce costs, but lasers typically require a metal-hermetic package with a sealed glass window because these devices can be quite sensitive to water, oxygen, and other atmospheric constituents. Telecom photonic packaging, however, requires the extreme reliability packaging that is usually a metal enclosure intended for 20 to 30 years of service. These packages are very expensive, but the cost of penalty is somewhat offset by the high cost of many of the optical components and the high number that may be used in a single package. Telecom optoelectronics systems probably should not be compared to a MOEMS device that is typically packaged as a single integrated component. Telecom optoelectronics has not been able to integrate, and for sound reasons having to do with the physics of light, and a packaged product will often have over 100 discrete components that must stay precisely aligned. Telecom has a fully developed set of specifications and tests methods for optical packages but the industry has had decades to establish them. MOEMS devices are still at an embryonic stage; there are few standards and even test methods are not agreed upon.

Since many of the MOEMS packages will require full hermeticity, the window seal must be designed to be hermetic. Seals will include glass to metal, ceramic, and plastic (small leak rate). Glass-to-metal bonding can employ soldering but the glass must have a metallized boarder. Glass can also be bonded directly to metal, but the glass must be melted and this can deform the window. Another option is to use a lower melting glass bonding material, like glass frit to produce a “frit seal.” However, direct glass-to-metal bonding is more complicated than soldering since special highly controlled low oxidation atmospheres are required, and a small amount of metal oxide assists wetting by the glass to ensure good bonding. Reliability requires that the CTE values for each material are fairly close to preventing thermomechanical stress. Unless there is an approximate match, there must be some mechanism to accommodate differential expansion, but using nearly matched materials is preferred.

Nonhermetic and near-hermetic seals are evaluated since processing can be quite simple, more versatile, and less costly. Texas Instruments began with polymer adhesive seals for glass, switched to metallurgical types, and then reevaluated them more recently. As of yet, they have not moved in that direction apparently because leak rate data suggests a small but measurable reduction in lifetime. However, organic adhesives can be viable and candidates include: thermoset epoxies, silicone-based glass-reactive compounds, UV curable adhesives, and thermoplastics that can be bonded using laser sealing. LCP film and other good barrier plastics should be considered as a preform adhesive that can be applied between the glass lid and ceramic, or metal-hermetic-type enclosures. Laser energy can be directed through the glass to melt the plastic film and bond the two surfaces together. Since epoxy is apparently too leaky, LCP may provide enough barrier improvement to be viable. Several companies specialize in adhesives for bonding glass. While polymer seals are nonhermetic, the package can still have a relatively low leak rate since the total exposed area is small and the adhesive pathway is long.

Once the sealing process and materials have been selected, testing is required to (1) measure the hermeticity level of the seal and (2) verify that the seal remains intact after thermocycling. The first test that should be performed on the package sealed is gross leak to detect any faults in the sealing process. This test also can locate the leaking area that can be localized, such as a corner, and give clues about the problem. A qualitative approximation test can be done by immersing the package in heated liquid; perchloroethane ("perc"; dry cleaning fluid) can be used if the more expensive fluorinated liquid is not available that is specified in MIL-STD-983F Method 1014.11 condition C1. However, the simpler test may miss smaller leaks. The next test, after ensuring that there are no gross leaks, is a fine leak test using helium; MIL STD-883F, METHOD 1014.11, condition A. After passing both leak tests, the package should be subjected to thermal cycling and the MIL-STD-883F that requires 55 to 125°C, for 1000 cycles, is the *de facto* standard and a reasonable starting point, unless there are other requirements set by the application. The gross leak and fine leak tests should be performed after thermocycling. Once again, the gross leak test is valuable for pin pointing the leak location that may give clues as to what is happening.

A light pipe, especially optical fiber, can also be used as the light path between device and the outside and this scheme is used extensively for telecom packaging. Optical fiber can be introduced into the package through a metal ferrule with a gas-tight seal created by soldering a joint around the glass fiber. The glass must be metallized in the region where the solder joint will be formed, and this is done with either vacuum coating or plating. The package is tested using the gross leak and fine leak tests. The same type metal fully hermetic package could

be used for MOEMS, especially for a telecom switching module, but is very expensive. Polymer seals can also be considered by a finite leak rate that is almost certain.

3.7.2 Maintaining optical clarity

The optics and their pathways must be kept optical clear during the operation of the device over its lifetime. Moisture can be expected to “fog” lenses and even attack optical elements making low moisture maintenance a likely requirement, at least with the common optical elements. There can be a problem even if the package is hermetic, unless the system is well dried before sealing. Predrying by heating is common. Moisture getters can be added to the inside of the package and this is done in the TI DLP package. Moisture getters are desiccants that bind water. Combination getters such as particle-moisture types are recommended for MOEMS.

3.7.3 Dimensional stability

Since MOEMS chips are sensitive to stress, the package system, as with other MEMS devices, should reduce stress as much as possible. But optical systems can be even more susceptible to dimensional change effects that alter the light path or optical characteristics. A MOEMS package may require low TCE materials or a platform with low expansion.

3.7.4 Thermal management

Depending on the function of the MOEMS device, thermal management can become very important. The DLP, mentioned earlier, is exposed to strong radiation that causes significant heating. The DLP package is designed with heat removal in mind and a large heat sink is positioned at the base of the package. Figure 3.24 shows the design of TI’s DLP

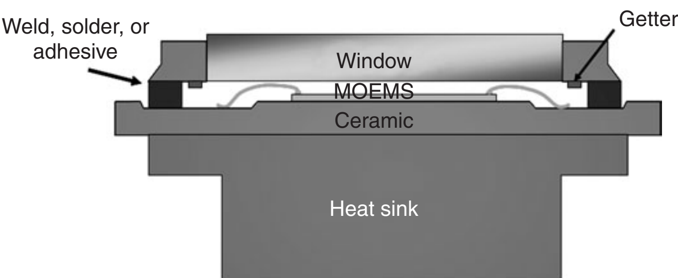


Figure 3.24 DLP package.

package with glass window and heat spreader. The ceramic header consists of an Al_2O_3 ceramic base with metallization for interconnections and copper or silver and a brazed Kovar seal ring. The hermetic window assembly utilizes a glass-to-metal seal of polished, AR-coated Corning 7056 glass and gold- or nickel-plated Kovar frame. The window sealing process is parallel resistance seam welding to the ceramic header seal ring. Future development has the goal of reducing cost of materials and processes.[16]

3.7.5 In-package dynamic alignment

Telecom optoelectronics modules are very expensive compared to pure electronic equivalents and much of the cost resides in the package. Manual alignment of fiber and optical elements adds considerably to the assembly cost. One scheme that is being proposed is to place a dynamic aligner inside the package. MEMS, of course, is the ideal technology for the scale required. One such aligner has been developed and is offered for license by Boeing. Boeing Company has designed, developed, and demonstrated a fully integrated wafer level processed active fiber optic microaligner. The device can move in the *X*, *Y*, and *Z*-directions to move fiber or another optical objective into perfect alignment. These devices are capable of large force and displacements with submicron accuracy. Fiber optic alignment and bonding to discrete optoelectronic and photonics devices requires alignment with submicron precision in less than 0.1 min/6 s. An application for active fiber microactuators is in package alignment and coupling of single-mode fiber optics (single or multiple fibers) to laser diodes in small packages. Other applications include single-mode fiber optic back-plane connectors and multiple fiber optic connectors. The patented[17] technology is available for licensing.

3.8 Packages for Materials Handling

In the future, MEMS devices will deal with more material handling and not just ink as seen with ink jet devices. In the case of ink jet printer modules, the fluid reservoir is connected to the MEMS jetting chip and the electrical connection is created with a remarkable pressure type connector that uses a specialized package based on flexible circuitry. But, the ink jet system is the only well-established technology for MEMS material handling chips. We need to look at other materials, different needs, and innovative design concepts. MEMS can likely perform every function and carry out every important process found in the macroworld of manufacturing. Factories handle more solid materials than any other form of matter, but fluids and gases are also important. Fluidized solid conveyance, common in manufacturing and even in agriculture, can be scaled to a level where MEMS can mimic these processes. Nanopowder technology should allow

MEMS to deal with solid matter including transport through conduits. Analytical methods also sample the three forms of matter, and we can expect MEMS and MOEMS analyzers to do the same.

3.8.1 Design concepts

Design should start with a "clean slate" approach, especially for an area like MEMS that is really just beginning. But after the conceptualization stage, every attempt should be made to adopt existing processes if possible. The next level, when no process will work is to look at new processes with existing packaging equipment. Inertia to change usually has economic routes, so utilizing existing lines even with different materials and processes is more readily accepted. But when the situation requires a truly new concept, material, and machine, the result will require a high reward for success if one wants to gain support. But this is the stuff from which start-ups are born.

3.8.2 Fluidic systems

The most basic fluidic MEMS system is the ink jet printer cartridge that has become nearly ubiquitous. The ink jet printer cartridge is one of the most optimized pump and reservoir constructions ever devised. A single MEMS jetting chip can have 1000 jet ports and up to four separate fluid containers and deposit on demand at incredible rates and all with high precision. But much more complicated fluid-handling devices have been made and we can expect very sophisticated and highly integrated systems to emerge. At least 50 companies are claiming to be involved in fluidic MEMS development. Considering all of the industrial processes where fluids are pump controlled, and manipulated, this area of MEMS should become one of the most important in the future. Fluids are subjected to hundreds of processes that include spraying, pumping, heating, cooling, freezing, pressurizing, mixing, evaporating, vaporizing, pyrolyzing, depositing, irradiating, filtering, separating, centrifuging, distilling, thickening, thinning, coloring, decolorizing, atomizing, emulsifying, and so on. MEMS technology will be able to produce all of these processes and many are already reported. But the individual processes can be integrated to carry out complex analysis, synthesis, and general manufacturing. Fluid handling packages will become the most interesting challenge encountered.

3.8.3 Gas/airborne agent analyzers

MEMS gas-handling chips will have similar requirements to the liquid-handling systems, but gases are generally easier to deal with than liquids that offer more resistance to flow and undergo much greater changes in rheology compared to the miniscule changes observed with gases.

Analyzers will be one of the largest classes of gas-handling products. Packaging will need to have gas-tight couplings and some will require a quick-connect-disconnect format. Much of the work in fluidic coupling will apply here.

3.8.4 Nanoscale particles and MEMS

Nanoscale powders should be able to be transferred through microplumbing similar to that designed for fluids. Design rules could require smoother "pipes" and more gentle turns. Technology long used in the macroworld may be applicable.

3.8.5 Selectivity for ports

The need to access certain external agents while eliminating others will require selective entry ports. Filters, including those made of nanomaterials like carbon nanofibers, will be valuable for the MEMS scale. Various types of separation membrane technology should also be applicable. Even getters placed in port areas may be useful. Packages may require designs where selective ports, or couplings, can be replaced in service.

3.9 NHP Beyond MEMS

MEMS packaging technology will become the model and prototype for nanotechnology needs. While addressing the special needs of MEMS, the packaging concepts, materials, and processes that emerge are extremely versatile compared to electronic packaging. MEMS is so versatile that packaging solutions are also versatile and applicable to other areas. MEMS packaging will therefore pave the way for nanoelectronics packaging, and other areas that will include nanomechanical devices. Nanoelectronics has already developed laboratory versions of transistors, triodes, new classes of lasers, and optoelectronic devices. While we may not know how they will be packaged, all will need electrical conductors and insulators. But hermeticity requirements may be lower than for some of the MEMS and MOEMS devices. NHP developed for some of the MEMS devices could turn out to be the ideal technology for nanoelectronics, since much will be based on organic devices not all that different from today's polymers. Chapter 6 will cover nanotechnology in more detail.

References

1. MIL-STD-883F, 18 June 2004, Superseding, MIL-STD-883E, 31 Department of Defense, Test Method Standard, Microcircuits, AMSC N/A FSC 5962.

2. Tseng, A. A., Tang, W. C., Lee, Y.-C., and Allen, J., "NSF 2000 workshop on manufacturing of microelectromechanical Systems," *J. Mat. Processing & Manufacturing Science*, Vol. 8, No. 4, pp. 292–305, 2000.
3. Harper, C., *Electronic Packaging and Interconnection Handbook*, 3d ed., McGraw-Hill, New York, 2000.
4. Occhionero, M. A., R. W. Adams, K. P. Fennessy, and R. A. Hay, "Aluminum Silicon Carbide (AlSiC) for Thermal Management Solutions and Functional Packaging Designs," *Proceedings of the Annual IMAPS Conference*, San Diego, CA, October, 1998; Conference (GOMAC), *Digest of Papers*, Vol. 20, pp. 454–456, November 1994.
5. Novich, B. E., and R. W. Adams, "Aluminum/Silicon Carbide (AlSiC) Metal Matrix Composites for Advanced Packaging Applications," *Proceedings of the 1995 International Electronics Packaging Conference, IEPS*, San Diego, CA, September 24–27, 1995, pp. 220–227.
6. Sahakian, V., "Integrated Circuit Chip Sealing Assembly," U.S. Patent 4,907,065, March 6, 1990.
7. Yamamoto, K., et al., "Hermetic Sealing of Wafer Scale Integrated Wafer," U.S. Patent 5,150,196, September 22, 1992.
8. Roberts, Jr, C., et al., "Method for Separating Circuit Dies from a Wafer," U.S. Patent 5,362,681, November 8, 1994.
9. Adams, V., et al., "Semiconductor Wafer Level Package," U.S. Patent 5,323,051, June 21, 1994.
10. Alfaro, R., "Grid Array Masking Tape Process," U.S. Patent 5,435,876, July 25, 1995.
11. Martin, J., "Covers for Micromechanical Sensors and Other Semiconductor Devices," U.S. Patent 5,610,431, March 11, 1997.
12. Spooner, T. R., and Harney, K. P., "Method and Device for Protecting Micro Electromechanical System Structures During Dicing of a Wafer," U.S. Patent 6,555,417, April 29, 2003.
13. Einstein, A., *Reader's Digest*, Quotable Quotes, p. 42, July 1977.
14. Wetzel, K. E., "Low Cost CCD Packaging," U.S. Patent 6,011,294, April 8, 1996.
15. Ko, W. H., "Packaging of Microfabricated Devices and Systems," *Materials Chemistry and Physics*, Vol. 42, pp. 169–175, 1995.
16. Faris, J., and T. Kocian, "DMDTM Packages—Evolution and Strategy," *Texas Instruments Technical Journal*, Vol. 15, No. 3, pp. 87–94, 1998.
17. Haake, J. M., U.S. Patent 5,606,635, February 25, 1997; 5,602,955, February 11, 1997; 5,553,182, September 3, 1996.

This page intentionally left blank

Chapter

4

MEMS Packaging Processes

This chapter will describe processes that are being used today and others that can be valuable in the future for assembling *microelectromechanical systems* (MEMS) and *micro-optoelectromechanical systems* (MOEMS) devices into packages. Package additive and sealing processes, which are a unique aspect of MEMS packaging not found in other technologies, are also covered. Many processes are standard assembly methods that are used for electronic devices and that is the intention. We should endeavor to take advantage of the well-established existing packaging infrastructure whenever possible. There is a high cost penalty for ignoring established methods and employing nonstandard equipment if it is not really necessary. Process modification is a different issue. Changing the sequence or adding steps that can be handled by existing equipment and process methods is quite acceptable. Some high-volume MEMS packaging has been able to tap into the existing methods to use packaging lines, even though the package designs and materials are new and different. But there will be some device packages that require different methods and equipment to accommodate the special needs of MEMS devices. MEMS ink-jet chip packaging is a good example of a specialized design and process. The flex-based package-circuits are unique in the world of packaging, although existing materials, processes, and equipment have been used with some modification.

MEMS inertial sensors were first packaged in fully hermetic ceramic enclosures but the cost of the package could exceed that of the device. Device fabricators were forced to lower margins and sometimes sell at a loss to open up markets while working on better solutions. More recently, MEMS inertial sensors have moved to plastic packaging that helps meet

Copyright © 2005 by The McGraw-Hill Companies, Inc. Click here for terms of use.

price point targets to open up higher volume consumer markets. Accelerometers and gyroscopes are good examples. Many are now packaged using conventional methods, but this requires that the MEMS devices first be protected by capping to prevent the encapsulant from making direct contact with the dynamic mechanical parts. The capping process allows the protected MEMS chips to be overmolded with standard epoxy molding compound just as if it were an ordinary electronic chip. But even with capping, some devices perform much better in a cavity style package and this fact has inspired the development of processes to produce low cost plastic cavity packages as well as simpler lid sealing processes.

More recently, thermoplastic injection-molded cavity packages have gone into production for MEMS gyroscopes that are too sensitive to stresses that resulted when they were first evaluated in transfer overmolded packages. But the plastic cavity packages can be manufactured on standard injection molding machines. The resulting packages can also be assembled on standard lines although one or two steps must be added. MEMS chips can be attached and wire bonded with conventional die attach adhesives on existing wire bonding equipment. However, lid seal is a less common step for plastic packaging lines and this becomes an added step. The lids can still be sealed by dispensing adhesive onto the lid bottom, or package edges using existing dispensers initially designed for die attach adhesive application. Since no new equipment was needed for lidding, there has been no real "push back" from the packagers. However, *laser sealing*, even if it is the best way to assemble plastic lids, would be a problem. This type of equipment is not readily available in plastic packaging assembly lines, although it may be found on more specialized *ceramic hybrid* lines and is widely used in printed circuit board facilities. The large packaging foundries would need an incentive to add such equipment and process steps. The MEMS device manufacturer would most likely need to make an investment or guarantee some minimum level of business. It is also not yet clear who will assemble lower volume, more specialized MEMS packages. While dedicated MEMS packaging foundries are advertising services, smaller MEMS companies, including Fabless, may decide to become packagers.

Some package designs for MEMS will be so unique that new processes and equipment will be needed. Capping, for example, is a unique wafer-level process that requires special application equipment and saws. The MEMS device manufacturers will either have to set up and run this type of wafer process or convince a packaging foundry to work in partnership. But if each device maker uses a proprietary capping method, a good possibility, then packaging foundries will find it difficult to establish standard capping processes. In addition to known methods, a few theoretical concepts are included in this chapter that could be useful in the future or in stimulating additional ideas among readers.

TABLE 4.1 MEMS Packaging Foundries

Company	Location
Advanced Custom Sensors	U.S.
Amkor	U.S., Asia
Applied MEMS	U.S.
Handy & Harman Electronic Materials	U.S.
Honeywell	U.S.
Hymite	Denmark
Kyocera	Japan
MCNC Research and Development Institute	U.S.
MicroAssembly Technologies	U.S.
Micro Pack Technologies	Korea
Nantong-Fujitsu Microelectronics	China
OKI Electric Industries	Japan
Olympus MEMS Foundry	Japan
Quantum Leap Packaging	U.S.
Rohm & Haas Electronic Materials	U.S.
SensFab Pte Ltd.	U.S., Singapore
Senzpak	Singapore
Teledyne Microtechnology Center	U.S.
Ziptronix	U.S.

Although there are several MEMS device foundries, a MEMS packaging industry is not yet well established, but this is still likely to occur. However, there are some companies that are dedicated to MEMS packaging and others claiming to have an interest and capability. Table 4.1 is a list of companies that may be of help in getting MEMS devices packaged.

4.1 Release Step

The final wafer-level step in MEMS fabrication is “release,” which unlocks any movable structures. This is typically done by etching the sacrificial structure. Etching can be a wet chemical process or a dry “energy” method. Several companies, such as Chemitronics Co., Ltd, sell dry etchers just for the release step. Once the sacrificial structure is removed, the parts made of permanent material are now free to move if that was the intent of the design. After release, devices are much more vulnerable and susceptible to damage by mechanical shock and decidedly predisposed to disabling contamination. Packaging is often done as the next step immediately after release and without shipping the released wafer to another location. Any wafer-level prepackaging, such as capping, is done next. This brings up the logistics issue. Some contend that the MEMS wafer should be shipped to the packager before release, and that the packaging foundry should carry out the release step.

This may be acceptable since some of the large packagers now run wafer-level processes such as *flip chip bumping*. For our discussions, the release step will be considered as a part of the packaging process.

One alternative, at least for inertial sensors, is to "cap and ship" although the parts are still moderately sensitive to mechanical shock until packaged. However, the packaged device can still run into problems with rough handling that can cause moving parts to stick together due to stiction. The device is further protected after assembly to the board, but dropping the board on edge can cause damage. The assembly is finally safe from most damage after it is placed into the final full system that may be the vehicle in the case of accelerometers. Perhaps the most valuable attribute of the capped wafer is that the MEMS active zone is protected from contamination.

Etch release is one of the most critical processing steps for many MEMS devices since the sacrificial layer must be removed with precise control. The amount of material removed can be small and can vary from a few hundred angstroms to a few microns. Etching must be predictable to provide a uniform undercut on devices. The sacrificial, or top release layer, is typically *silicon dioxide* (SiO_2), and fluorine chemistry is commonly used because of its high reactivity with SiO_2. The yield can certainly be impacted by the release step and this adds to the logistics issue. The MEMS foundry will probably want to control this step to be sure of the yield. So, should the device fabricator become the packager?

The release step requires thorough cleaning to remove etchant, dissolved silica (or other sacrificial material), tiny solid debris, and any other sacrificial by-product that may remain. Stiction between movable parts is a serious concern during release. Stiction occurs when surface adhesion forces are higher than the mechanical restoring force of the microstructure, and is almost always the result of parts being forced into direct contact. Aqueous cleaning sets up a situation that strongly promotes stiction. As the device is removed from the aqueous solution after wet etching of sacrificial layer, the liquid meniscus formed on hydrophilic surfaces evaporates and shrinks to pull the microstructure toward the substrate—stiction is likely. This phenomenon is shown in Fig. 4.1. One approach to circumvent the stiction problem is to switch to bulk micromachining, but this is less capable and less versatile than surface

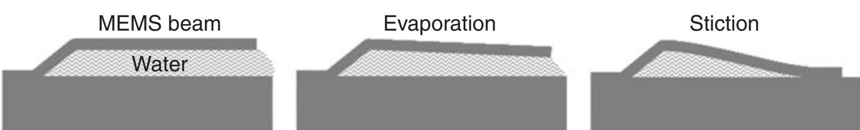


Figure 4.1 Stiction induced by aqueous cleaning.

micromachining in terms of device function. A better approach is to use special cleaning procedures that can prevent the common "wetting-drying stiction" phenomenon, and this is discussed next. Even with dry etching, a wet cleaning step may be required.

4.1.1 Stiction and cleaning

Let's look at stiction in more detail. Stiction can be defined as the adhesion caused by strong interfacial forces between contacting crystalline microstructure surfaces. In our context, it's the unintentional adhesion of MEMS surfaces and is irreversible within the limits of the MEMS actuation forces and one of the more persistent and pervasive problems with MEMS device production, packaging, and handling. Capillary forces from liquid cleaners pull parts together as the liquid in contact with adjacent surfaces slowly evaporates. This liquid contact phenomenon is due to Laplace pressure differences and surface tension forces that produce an attractive force. While the capillary forces themselves are enough to cause sticking, evaporating liquid is an even greater problem. The volume reduction as the liquid evaporates can produce enough force to collapse fragile suspended structures. The diminishing drop pulls the MEMS surfaces closer and closer until they touch and lock. But this can also damage devices and promote the adhesion that results from the Van Der Waals and electrostatic forces.

The release–stiction problem may be reduced and even eliminated by dry etching, use of nonaqueous cleaners, and by employing supercritical carbon dioxide (CO_2) for drying. Supercritical drying is a very common way of reducing capillary forces in the drying step. The MEMS devices are dried in liquid CO_2 that is raised to its supercritical point by adjusting pressure and temperature. A meniscus does not form during drying and the surfaces are not pulled together. Parts can also be chemically treated so that device surfaces resist sticking even if contact occurs. This treatment step is usually a part of the packaging process, but it would make sense to incorporate it in the drying step where possible.

Russick and coworkers have demonstrated that supercritical CO_2 extraction can be used for solvent removal to successfully release compliant and fragile surface MEMS structures on silicon wafers. These structures that have been released and cleaned include single gear microengines, bridges and cantilever beams, pressure transducers, and comb drive actuators. The supercritical fluid has negligible surface tension and can remove solvent even in capillarylike spaces as narrow as a few nanometers. Supercritical CO_2 has been shown to reproducibly dry components and structures, including cantilever beams up to about 1000 nm in length, without collapsing. His very detailed paper describes equipment and the extraction process.[1]

4.2 Singulation; Sawing and Protection

Wafers with electronic devices are singulated by sawing with diamond blades using a process that has not changed much in decades. MEMS present a special problem. While electronic wafers are relatively smooth and the microstructure is buried below the surface, MEMS products can be three-dimensional (3D) with delicate exposed parts and various openings that can trap fine particles. The MEMS active surface must be protected from contamination during singulation. One method is to use wafer-level packaging methods that seal off the MEMS surface before sawing as mentioned earlier. Capping is the most common method and it will be covered in the next section. However, not all MEMS devices can be capped since they may require access. But if no permanent protective structure is to be applied, then a temporary protection scheme must be used unless a novel totally clean singulation process will be used instead of sawing. Researchers continue to investigate several singulation techniques and some approaches could prove effective enough to replace sawing.

The face of the wafer can be bonded to specially constructed singulation tapes. MEMS pioneers, like Analog Devices, have successfully used a temporary tape approach that is now described in their patent.[2] This MEMS process involves attaching the wafer to a thin plastic film, but instead of mounting the back side of the wafer to the film, the top surface containing the MEMS movable elements is mounted to the film. Since the MEMS chips are often very fragile, just prior to mounting the wafer, relief holes are punched into the film with a size and relative position corresponding to the active MEMS locations on the wafer. The holes must match up with the microstructures on the active face of the wafer. Dimensional control is achieved by attaching the film to a frame holder prior to hole formation and wafer bonding. Holes corresponding to the microstructures on the wafer are fabricated by mechanical punching or lasing. The wafer is then precisely aligned to the film so that the holes are over the microstructure regions. The film and the wafer are then brought into contact for bonding. The MEMS mechanical areas on the wafer do not make contact with the film because of the relief holes in the film.

An additional set of alignment holes are formed in the film during relief hole fabrication. These holes are placed with precision and aligned relative to the microstructure holes such that the position of the streets on the wafer will be precisely known relative to the alignment holes when the wafer is mounted to the film, even though the streets will not be visible since the wafer will be mounted upside-down on the film. The sawing station camera can use the registration holes for aligning the saw blade to the streets. Alternately, ink dots or other indicia may be placed

on the film or elsewhere instead of alignment holes. Figure 4.2 shows this singulation protective process.

A second thin plastic film can be adhered to the back side of the first plastic film to seal off the punched holes to protect the microstructure from water and dust. After the second layer of film is adhered to the first layer of film, the double film assembly can be placed onto a dicing pallet in a sawing station with the wafer upside down. The camera on the sawing station observes the wafer and the pattern recognition software determines the position of the alignment holes. The pallet is then moved to align a street with the saw blade. A normal sawing operation is then performed. The water jet spray and contamination particles do not contact the microstructures because they are sealed within the film.

The film-wafer frame assembly is then delivered to a pick-and-place package assembly station. The assembly is placed into the pick-and-place station with the wafer upside down. A needle assembly is raised under the film frame assembly to press against the film and lift individual dies as the film flexes. This special needle assembly is made up of a cluster of ball point needles that are positioned to make contact only with the critical locations on the MEMS wafer.

The backside of the wafer can also be protected with temporary coatings or films. Water-soluble protective coatings can be deposited over the MEMS structure and then removed after the die sawing process. Materials can be sprayed on and then hardened, or partially hardened. The protected wafer may still be attached to conventional dicing tape.[3] In still other examples, special two-layer dicing tape systems are used that encapsulate the MEMS structure for the die sawing process. Two wafers are temporarily mated together, face-to-face, just for the singulation step.

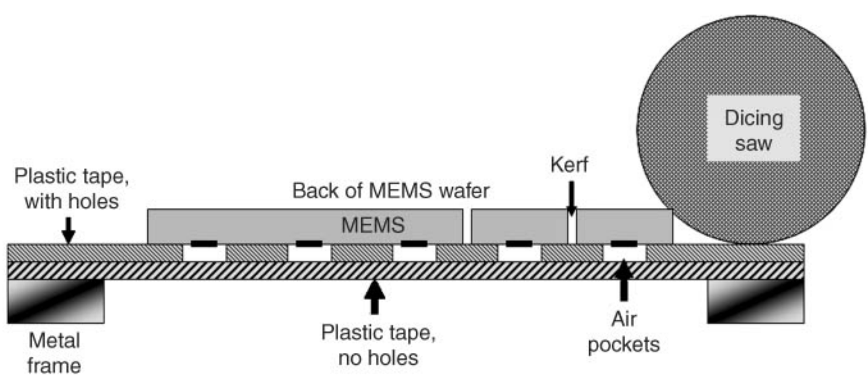


Figure 4.2 MEMS wafer protection for singulation.[2]

Laser scribing has been studied as one of the most obvious and clean singulation processes for MEMS. The wafer is usually scribed and later separated by snapping the “streets.” Some methods laser scribe before the release step. Another method involves etching grooves between devices (streets) during the normal MEMS fabrication processes. Scribing can also be done with a precision diamond tool; scribe groves ~3 to 5 μm in a 20-μm street. Wafer snapping methods provide a precise means of die separation with minimal debris. Most approaches are back end methods that temporarily protect the wafer during sawing.

A typical process may involve spin-coating (a protective material) onto the back and front sides of the device wafer after attaching it to a “holder” wafer. The holder wafer is then removed and mounted onto a dicing tape where devices are singulated by standard dicing. Individual dies can then be picked from the tape and protection material removed using wet and dry cleaning methods. A singulated die with fragile device components is picked from dicing tape before removing protection layers.

The simplest process is to apply wafer tape to both sizes and saw, although more specialized films are now used that have the right properties for sealing, sawing, and removing without damage to the devices. A protective method must be selected that is compatible with the particular devices in the wafer, and there is presently no universal method.

Texas Instruments (TI), with considerable MOEMS manufacturing experience, uses a partial singulation process before the release step. Their *digital light processing* (DLP) wafer is first protected with a plastic film. Standard sawing of the released wafer would destroy the delicate mirror superstructure as the dicing fluid impacts the wafer. After applying a protective film to the active side of the wafer, sawing followed by cleaning can be accomplished without damage. There is also a plasma undercutting step just after mechanical sawing as well as a passivation process. Then the wafer is ready for the release step, which uses an ash process to remove the sacrificial layers. The wafer can now be tested and marked in a class 10 environment. The final step before packaging is complete singulation using a proprietary process that produces essentially zero contamination. This step appears to be a mechanical snap process. During operation, the mirror spacing drops from 1 μm down to 0.2 μm so that a very small solid particle can immobilize a mirror and thus “kill” a pixel.[4]

4.3 Capping Approaches

While placing a cap over the active MEMS area may seem like a clever, novel, and refreshing idea, it is has been around for quite a while with so many inventors that its origin is a bit obscure. The large MEMS manufacturing companies who make inertial devices all employ capping.

Although there are a number of patents, none of the *intellectual property* (IP) holders seem to be pursuing legal action in these "muddied waters," at least for the moment. There are several constructions and many more processes. There are several levels of caps too, but they can be grouped into dielectric-only and pass-through conductor types. The early capping patents for MEMS were filed in the late 1980s and early 1990s by some of the veteran semiconductor companies who have worked on MEMS for a decade or more.[5–9] Many improvement patents have also been filed since then.[10] With the considerable prior art, it is surprising that so many universities seem to be working in this area today and reinventing the cap. A search of the Internet will reveal hundreds of papers, press releases, patents, and advertisements for "MEMS capping."

There are a few novel capping ideas under investigation, however. One involves forming cap patterns in a template—probably a silicon wafer—and using this donor wafer as a mold to form an array of microcaps that can be transferred to the MEMS wafer. The caps could be bonded with a metal ring seal that may be produced in situ. Intel, Sandia, and UC Berkeley have been working on such schemes and there are likely to be others.

4.3.1 Dielectric caps

The most common process is to fabricate the cap array by etching a silicon wafer. This ensures an excellent *coefficient of thermal expansion* (CTE) match, at least for silicon MEMS wafers. The cap area is etched out and precuts can be made to assist singulation of the cap only. Cap-only singulation is done by sawing down to the cut. The cap array can be bonded to the MEMS wafer by any one of several methods, but the use of glass frit applied as paste is popular because a good seal results at a reasonable temperature (<500°C). The MEMS wafer with bonded caps can now be singulated and cleaned. But the protected wafer can also be shipped to a packaging foundry. The packaging foundry can singulate the MEMS wafer and completes that packaging assembly. Analog Devices, Inc. (ADI) has published and presented widely on the capping topic, and their process is now described in detail as the present *de facto* standard. Note that this is a dielectric-only cap with no electrical feed-through vias. ADI points out that a cap with feed-through vias would be larger and could require a bigger chip. They feel that the cap without feed-through strategy gives the best overall economics, functionality, and reliability, at least for ADI's accelerometers and gyroscopes. Figure 4.3 shows the capping process.

One issue with capping is concern about the high temperature required for some processes. Fusing glass frit can require nearly 500°C using a conventional oven process. although some glass seals can be formed at as low as 430°C. Several researchers have investigated lower temperature

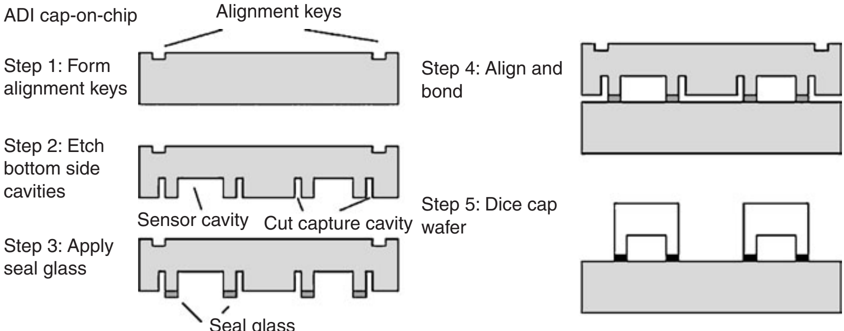


Figure 4.3 ADI capping process.

methods. Microwave Bonding Instruments, Inc. (MBI), for example, has developed a microwave heat seal method specifically for MEMS products. MBI is a microchip assembly and packaging technology designer and equipment manufacturer that has patented technology to hermetically stack microelectronic and optical components and also increase the number of electrical interconnects. Silicon and quartz are essentially transparent to microwave energy allowing the radiation to pass through caps and concentrate the heating energy onto patterned metal lines. The metal patterns can be sealing materials that create a hermetic silicon-to-silicon (or quartz) bonds. Their patent specifically refers to MEMS and bonding of materials carried out with microwaves.[11] High microwave absorbing films can be placed within a microwave cavity that is a low microwave absorber. This strategy minimizes unwanted heating of the MEMS devices by producing very localized heating.

4.3.2 Caps with first-level interconnects

There may still be some undesirable features for dielectric-only capping process, but there are alternatives. One idea is to route conductors through the cap and connect them to wire bondable pads on the exterior of the cap. This would allow the cap and MEMS wafer to be sawn together. Figure 4.4 shows the concept. But while the singulation process

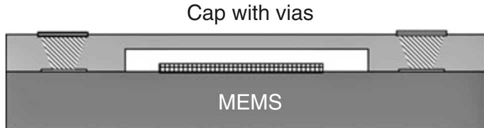


Figure 4.4 Cap with bond pads.

is now simpler, the cap making is more complex. And the issue of reliability is now introduced since there is the added interconnect of device wafer to cap. Furthermore, the wire bonding to the cap could be a source of unreliability from two aspects: The cap wire bond must be shown to have good reliability and the cap-to-device interconnect could possibly be damaged by the wire bond process.[12]

4.3.3 Caps with second-level interconnects

But if we look at the ultimate goal and then at the cap with feed-through vias, there is still another improvement that can be made. Why not add a second-level interconnect structure to the cap? Instead of wire bonding pads, we can add solder bumps or another means of direct connection to a *polychlorinated biphenyl* (PCB). The cap is now a part of the final package base and just needs to be inverted for assembly. Figure 4.5 shows a MEMS capped package with solder bumps that creates a wafer-level chip-size package. Some *chip-scale package* (CSP) feed-through concepts are found in the patent literature.

Several researchers and developers have come up with design concepts, processes, and even products for MEMS caps with electrical feed-through interconnect.[13] One idea, from the author, involves fabricating a silicon cap that has solid pass-through vias to the top of the cap that can terminate in several second-level interconnect formats; solder bumps, pin grid array, and even Legolike microstructures that can plug in and unplug. The cap has a first-level interface on the chip side that can form either a metallurgical junction with pads on the MEMS chip or a pressure type connection using a fine structure designed to penetrating into the MEMS pad metallization. Figure 4.6 shows the various interconnect surface structures for mating with the MEMS chip pads. These penetrating-connecting topographies could presumably be formed by MEMS fabrication methods.

Hymite offers commercial caps and provides capping services for MEMS that meet full hermeticity specifications as defined by MIL STD 883E. A silicon chip-size sealing cap provides an electrical interconnect

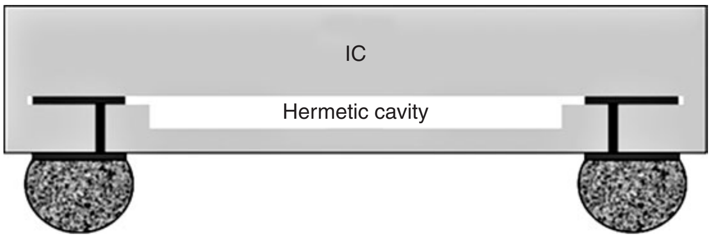


Figure 4.5 Cap with solder bumps.

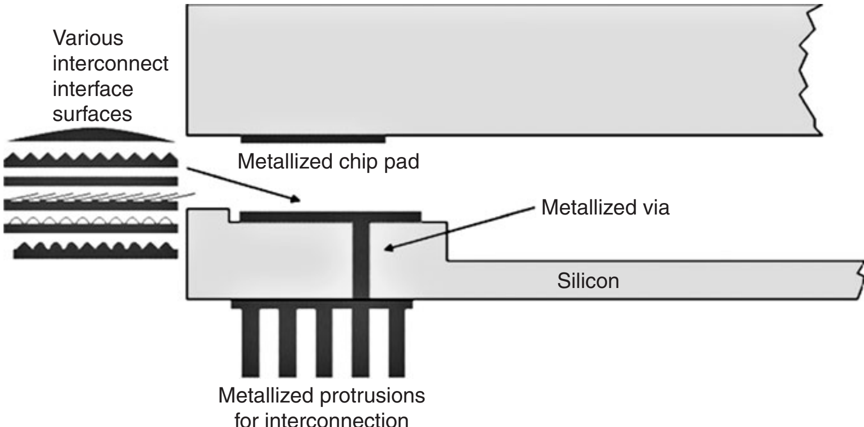


Figure 4.6 Cap interconnect designs.

using microvias. The HyCap is said to offer high thermal conduction and a matched CTE (if MEMS is Si) along with free space for the MEMS device. Figure 4.7 shows the cap construction. Integrated Micromachines, Inc. also has MEMS wafer-level packaging services. Their uHSeal is a wafer scale packaging technique that seals with a high-temperature fluxless solder and provides electrical connections. The Integrated Micromachines, Inc. (IMMI) claims to have successfully used their packaging technology for MEMS photonic cross-connect, reed switch, and gyroscope products. Ziptronix, which has received much press coverage for its wafer-bonding technology, claims to have a low-temperature covalent bonding method for wafer-scale, hermetic capping suitable for MEMS, MOEMS, and other surface-sensitive devices. However, available information is too limited for the author to assess this technology. A web search of *MEMS capping* located nearly 1000 hits, indicating how popular the approach has become.

Draper Labs has patented a capping process where posts are produced by etching, implanting boron or another etch-inhibiting dopant wherever

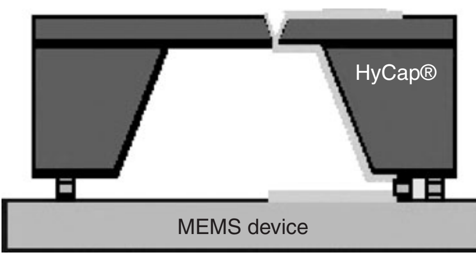


Figure 4.7 Hymite cap.

a post is desired. The dopant is applied to a depth that will correspond to the height desired for the post after etch by *reactive ion etching* (RIE)—the preferred etching process. The boron-doped silicon is electrically conductive so it can serve as the conduit. Various wafer bonding techniques can be used to mate the MEMS chip to the cap, such as anodic bonding or diffusion bonding. Diffusion bonding requires that the contacting surfaces be coated with an easily diffused material, such as gold, to create the electrical interconnects. Gold is the preferred metal and it can be applied by sputtering. The capped MEMS chip will be hermetic and can even be sealed in a vacuum to create a wafer-level vacuum hermetic package. Vias to the outside of the cap can be formed by laser drilling followed by vacuum metallizing. The second-level interconnect can be any of the common types including solder bumps for flip chip, conductive adhesive bumps, *tape automated bonding* (TAB), and others.[14]

4.4 Die Attach

Die attach is typically done with polymeric adhesive for most electrical devices and most MEMS. The MEMS devices are more sensitive to stress; therefore a low stress adhesive is recommended. In fact, an accelerometer may interpret stress as acceleration. Even if the phantom stress can be adjusted out, the device will be less sensitive, and the motion versus signal characteristics may no longer match the expected responses. The most common approach is to use very low die-attach adhesives based on silicone polymers. These materials are described in Chap. 5 along with others that are suitable for MEMS.

4.5 Wire Bonding

Wire bonding for MEMS devices is fairly standard, requiring no modification. Standard bonders are used and essentially have no differences, except that a cavity package when used requires more careful setup because of the constraints of the package walls. Die bonder on a high-speed line operates without any sidewall interference. When a nonhermetic cavity package is used, it may be necessary to encapsulate the die bonded area to prevent corrosion. The step of adding encapsulant or gel is not really a part of die bonding, however.

4.6 Flip Chip Methods

Flip chip or *direct chip attach* (DCA) offers some advantages for MEMS and MOEMS. The DCA joint provides a built-in separation distance, or stand-off between the active face of the die and substrate. DCA can utilize many kinds of joining systems from common metallic solders to

low-temperature conductive polymers. DCA can be divided into four subdivisions; (1) device, (2) bumps, (3) joining material, and (4) underfill. The bump and joining material can be one and the same when the bump is solder. But a nonfusible bump like gold or nickel requires a joining material. The underfill is not required for all applications, but is almost always used when there is a thermomechanical mismatch between the chip and substrate, and/or protection from contamination is desired, and/or mechanical strength enhancement is needed. Use of a nonfusible bump ensures a minimum gap between the MEMS chip and substrate, if this is important. Electroless nickel bumps can be used with solder or conductive adhesive applied as the joining material. Conductive adhesive has the advantage of low temperature assembly (<150°C) that can be important for some MEMS devices.

Underfill is normally flowed under the assembled device to fill the entire gap. This may be undesirable for MEMS unless the mechanically active region of the die is protected by a cap or some other method. If the die remains unprotected, some other procedure will be required to exclude underfill contact in the active die face area. There are several possibilities: (1) underfill could have a high viscosity that prevents underflow, (2) substrate could have a recessed area, (3) antiwetting agents could be used to restrict flow areas. A solid, preapplied underfillor encapsulant could be used. Let's look at the options.

The first option for a restricted flow selective encapsulating method could be accomplished using a material called *damming compound*. This is a highly thixotropic encapsulant used in the dam and fill process for *ball grid array* (BGA) packages. For BGAs, the damming compound is needle-dispensed to form a "fence" around the perimeter of the package that retains low-viscosity fill type encapsulant that is intended to cover the die and wire bonds. The two encapsulant materials are cured together. The damming compound in a MEMS application could be applied around the perimeter of bonded flip chip as shown in Fig. 4.8. The very limited flow of this class of material, even when heated, should allow wetting to the chip, but there is no significant flow into the active MEMS area. The issue of underfill performance would be a concern, however. The underfill normally acts like a laminating adhesive to lock the

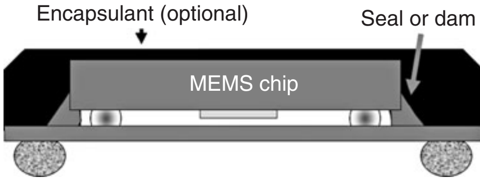


Figure 4.8 Selective underfill/encapsulant.

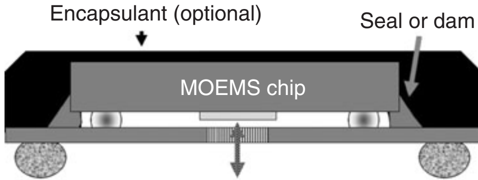


Figure 4.9 MOEMS package 1.

chip and substrate together, so that there is limited differential movement during thermal cycling. Would bonding around the perimeter be enough? The problem would be minimal if the chip and substrate TCE values were similar.

Flip chip might also be used for MOEMS. The package platform would need a light path that could be a port of fiber connection. It should be possible to create an optical coupling to the MOEMS device so that underfill could flow under the chip but be excluded by the optical arrangement as shown in Figs. 4.9 and 4.10.

Flow restriction might also be accomplished by adding a small dam to the "keep out" zone creating a recess, or by applying a low surface tension boarder. All of these methods have been successfully used in the plastic components area for containing *doming* or plastic lens fluids. Various switches and switch panels can be made more attractive and functional by applying a transparent liquid over the switch area and then hardening it into a dome. The material is kept in the desired pattern by embossing a tiny bead in the plastic to form a border or by printing a Teflonlike ink. In the case of the ink, a fluorosurfactant is added to a standard ink so as to reduce the surface tension to a low level that is not wet by the lens material. Such principles could be applied to retaining underfill as shown in Fig. 4.11.

Solid die attach adhesive has been commercially available for many years, as both B-staged thermoset and thermoplastic film and paste. The solid materials can be die cut or laser machined into any shape. A *picture frame* preform could be used here, which would only contact the

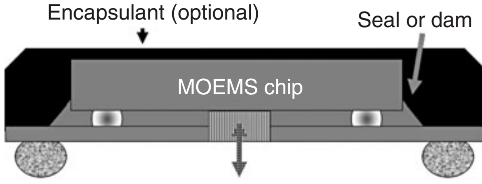


Figure 4.10 MOEMS package 2.

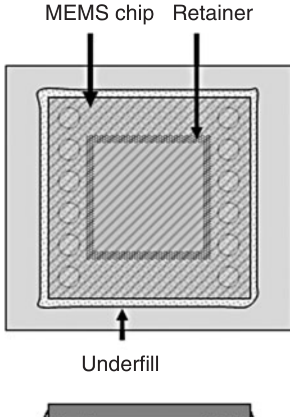


Figure 4.11 Retaining dam.

outer edge of the chip and not interfere with motion or optics. Such a material could be applied at wafer level. A release liner covering the opening could be left in place until chip assembly and perhaps serve as a tape carrier for automation. The thermoplastic films can be sawn along with the wafer and this process has been run in high volume for electronic wafers.

4.7 Tape Automated Bonding

Tape automated bonding (TAB) makes use of a flexible dielectric tape carrier that is actually a specialized form of flexible circuitry. The dielectric can be polyimide, *liquid crystal polymers* (LCP), or one of the several polyesters although polyimide is presently the dominant material. The dielectric layer can be 25 to 75 μm thick and the metal traces can be 37.5 μm (1 oz Cu), or much thinner, even down to 10 μm. The crucial feature for TAB is that free-standing, or cantilevered metal beam leads, are used to make the first-level connection to the chip. This sector is called the inner lead bonding area and the bonding process is accordingly known as ILB. The ILB area requires that an opening called "window" be formed in the dielectric to accommodate the chip as shown in Fig. 4.12. The beam leads extend over the window area to enable them to make contact with a chip placed inside the window area. The chip is placed under the window, or the tape carrier is moved and positioned over the chip. The chip pads and beam leads are aligned using automated vision control. A bonding tool is then used to connect the beam

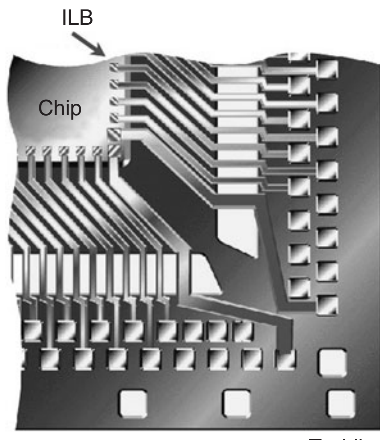


Figure 4.12 TAB ILB.

leads to the chip pads, typically with ultrasonic or thermosonic energy. The tool may bond one lead, one side, or the entire array all at once. Tessera uses a specialized bonding process where each lead is excised (broken away from notched section) and simultaneously formed while bonding to provide an "S" shape to accommodate any movement between chip and package. TAB and TAB-like product effective decouple thermomechanical movement between the chip and second-level interconnect substrate. The leads are normally plated with gold since this allows direct bonding to the aluminum pads. The chip pads may also be gold plated or even gold bumped. The flex chip carrier can be in the form of a tape that looks like 35-mm-camera film, the original form factor, although greater widths (70 mm) are also used. When tape format is used, the flex package must be cut from the reel in a process called excising. The resulting chip and die can now be bonded to substrate or a PCB. The outer leads that are released after excising are bonded by hot bar soldering or with adhesive film, and the process is called *outer lead bonding* (OLB). The TAB concept can be applied to MEMS and is especially valuable for jetting devices where the jet ports on the chip face must remain free of obstacles.

Today's flex-based packages often utilize the ILB portion of TAB but convert the OLB to an area array footprint, so that the package can utilize standard surface mount assembly. OLB assembly requires specialized processing and dedicated equipment. Keeping ILB and replacing OLB with SMT may seem small, but it has created a new package class that is very successful. IBM introduced the *tape ball*

grid array (TBGA) over a decade ago, but has applied this type of package to electronic devices with high thermal output. The package is made of polyimide and has a TAB-like ILB for connecting to the chip. The TBGA is a fan-out design with the OLB connection replaced by metal solder balls. Several other companies now supply tape BGA type packages. Tessera, founded by former IBM personnel, also converted TAB into an area array package, but used a fan-in configuration that allowed bumps to be placed under the chip making the package about the size of the chip—*chip scale package* (CSP). The Tessera μBGA package could be suitable for some MEMS chips. Figure 4.13 shows the standard μBGA. One possibility is to create an opening in the dielectric to accommodate access to the MEMS or MOEMS chip such as a free path to the PCB.

There is another innovative TAB-like construction and this design incorporates the ILB structure within an actual circuit to eliminate the OLB interconnect completely. A flex circuit is basically identical to TAB except for the window and beam construction. A TAB window and beam lead array can be formed anywhere within a flex circuit and this is much easier today than decades ago when these ideas first surfaced. Multiple TAB sites can be added anywhere with a flexible circuit. The author has referred to this configuration as TAB-featured flex (TABFF). Modern flex circuit processing makes it very easy to add TABFF. The ILB window in the dielectric can be created using laser machining or chemical etching; polyimide and LCP films lase well but also dissolve in very strong base so that multiple windows can be simultaneously produced. The TABFF approach has been used extensively for packaging MEMS ink-jet chips by Hewlett-Packard who worked on the flex development beginning in the 1980s and has substantial patent coverage including very recent patents. The bigger challenge was not the ILB, but rather the interface to the printer since very low cost was required. The present package-circuit has one ILB site for the MEMS jetting chip and one printer interface area. The circuit-package is wrapped around the ink cartridge taking advantage of the 3D configurability of flex. The ILB chip connection is made with a bonder from two sides (ink-jet chips have bond pads on two sides) of the chip and then the bond area is selectively encapsulated as seen in Fig. 4.14 close up. Encapsulation schemes for TAB are covered next.

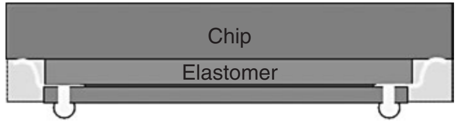


Figure 4.13 Tessera μBGA.

Figure 4.14 Ink-jet chip and connection.

4.8 Selective Underfill and Encapsulation

Once the MEMS chip is bonded to the TAB leads, the chip-to-lead frame connections must be protected from contamination, shorting, and mechanical damage during handling. Encapsulant is applied with an automatic needle dispenser that is programmed to cover just the interconnect area without getting encapsulant onto the active chip "jetting" zone. Some package assemblers use UV-cured encapsulants so that the material can be hardened quickly, for productivity and to ensure that there is no flow out into the jetting zone. Figure 4.15 shows the MEMS package-circuit.

4.9 Lid Sealing

Cavity style packages are normally sealed with a rigid lid that becomes the top of the package although some designs apply a boxlike enclosure to be placed over the package base or platform, so that the lid is more like a cap. Regardless of the configuration, the two parts must be joined

Figure 4.15 Ink-jet package.

together after the device is assembled and connected. Each class of material that includes metals, ceramics, and plastics can have different limitations in processing, but may have offsetting advantages in performance. The package performance requirements will also limit choices. For example, all materials can be sealed using organic adhesives, but the seal will not be hermetic. Solder can be used to form a hermetic seal with most materials, provided that there is a metal surface interface that will accept solder and withstand the heat. Soldering to nonmetallic lids require that glass, ceramic, or plastics are first metallized, but this can be an expensive task. We will first investigate sealing from the adhesive material, or bonding agent criterion, and then examine the other processes.

4.9.1 Thermal adhesive application

Thermally-cured adhesives, typified by thermoset epoxies, are the most versatile lid bonding agents. Epoxies bond strongly to most metals (especially if they have some oxide), plastics, ceramics, and glasses. In some cases, the substrate may need to be treated to improve adhesion but it is sometimes practical to make self-treating, or self-priming adhesives. Adhesives can be highly customized to improve properties for specific applications and compatibility with substrates. A simple example is to add an epoxy-silane compound to promote bonding to glass or ceramic adherents, and this is a very effective and low-cost approach. But the seal will not be hermetic when organic adhesives are used unless a barrier, which could include metal plating, is used. The adhesive can be applied as a thixotropic paste, a low-viscosity fluid, or even as a solid film. Pastes can be screen-printed onto the bottom of lids or the top edges of the package walls. Lids can be precoated with epoxy-hardener adhesive solution that is immediately dried, but remains reactive for bonding later. Solid epoxy-hardener materials can be dissolved in solvent to form this type of adhesive coating that can be quickly dried at a modest temperature that only evaporates solvent, but does not cause any appreciable polymerization. Later, the lid can be positioned onto the package body and sealed using heat and a small amount of force. Arrays of lids can be screen printed for efficiency. RJR Polymers, Inc. has developed such a system and offers coated lids and heat sealing equipment. RJR's preapplied B-stage adhesives have been applied to many different types of parts and lids for sealing seal cavity packages for optics and for MEMS. They offer services for applying both nonconductive and conductive adhesives to metal, glass, ceramic, and plastic materials. Some of the larger package makers, like Kyocera, will also provide lids made of glass, ceramic, and metal that are precoated with epoxy adhesive. These B-staged epoxies will slowly polymerize at room temperature and all have a limited shelf life, although it can be several months.

Parts can be stored in a freezer where the life time may increase to about 1 year.

Thermoplastic adhesives can also be used for lid seal. Thermoplastic resins are already polymerized and do not undergo additional polymerization upon sealing. Resins can be dissolved in polar solvents and applied by various means, although screen printing is not recommended because of the viscous and stringy nature of long-chain polymer solutions. Needle dispensing may be a better process. The coated adhesive is dried and hardened by solvent evaporation. Thermoplastic adhesives are more difficult to dry than thermosets, which only contain low molecular weight components. Thermoplastics can also be applied as preforms that are cut or stamped from film. The preform can be tacked to the lid or package using heat, or simply placed in position at the time of lid sealing. Thermoplastics typically require higher temperatures than thermosets since the materials must be raised to their softening point that can be as high as 350 or even 400°C, but the assembly time is very short since there is no polymerization involved, like with thermosets.

Needle dispensing is a more common adhesives application method for packaging assembly lines since this is the standard method for applying die attach adhesive making the dispenser a standard piece of equipment. The adhesive can be applied as a bead onto the bottom of the lid, or to the upper edge of the package. The lid is aligned to the package and heat polymerizes the epoxy-hardener mix to form a strong seal. Heat can be applied directly to the lid-package, or the entire package assembly can be moved into an oven. Laser heating can also be used but this is less common. Thermoplastic solutions are readily dispensed by needle, but the solvent should be evaporated before lid sealing so that the package interior will not be contaminated by organic solvents. Thermoplastics adhesives are often sold in versions that are specifically designed for needle dispensing. These types of adhesives have long storage lifetimes as pastes, unless filler settling becomes a problem (not common). Thermoplastic films can be but some suppliers will cut preforms to order. No cold storage is needed and the produce can be shipped by ordinary mail. Films, coated lids, and package bodies should be stored in sealed containers, or even plastic bags to prevent slow absorption of contaminants that may be present in the area. It's a good idea to bake-dry parts before sealing anyway.

4.9.2 UV curing of sealants

UV cured adhesives have been used on glass panels and lids for some time. Glass, and some plastics, will allow enough actinic radiation to pass through that it is practical to activate several types of radiation-cure

(rad-cure) adhesives. Both free-radical acrylics and cationic epoxies can be used. The commercial products for glass can be screen printed, needle dispensed, or jetted. Curing requires fairly simple equipment that is widely available and takes up very little space. A typical process is to apply adhesive to the glass lid in a border pattern, place the lid onto the package, and then expose to UV. The entire process takes only seconds, has no waste, and essentially no waste products. However, the resulting seal is not hermetic. But since the bond line can be thin and the path length relatively long means that the leak rate can be low. Texas Instruments pursued the idea of using UV-cured adhesives to replace soldering and reported that the lifetime of the MOEMS device, their DLP, was reduced by a small, but measurable amount that might still be acceptable.[17]

UV-cured adhesives can also be used for opaque lids since it is possible to formulate delayed cure materials. Cationic epoxies are especially useful here. Photocatalysts that are based on triaryl sulphonium salts of strong acids, upon UV-exposure release acids that polymerize epoxies. A small amount of organic base can delay the onset of epoxy polymerization by several seconds. Nitronium salts of super acids were found to have a built-in delay. Work done by the author indicates that the delay can be up to 1 min allowing more than enough time for exposure and applying the opaque lid to a package.

4.9.3 Laser sealing

Lasers have progressed to a level where they are affordable and easy to maintain, especially diode infrared and near-infrared lasers that can serve as an ideal heating source. Laser energy is highly controllable and can be localized so that the device being packaged is not significantly heated. The temperature level can be varied widely, but with good control, so that thermoplastic, ceramic, and metal packages can be sealed with lids made of almost any transparent material. Different sealing mechanisms may be used. Thermoplastics can be melt-bonded, thermosets can be cured, glass frit can be fused, solder can be melted, and metals can be brazed or even welded.

Extensive lid sealing research has been done with a Speedline Technologies prototype laser.[18–21] This unit has an adjustable power of 30 W near infrared power supply and diode array source from Coherent, Inc. with a wavelength of about 802 nm. The laser has a programmable X-Y positioning table and a vision system. A search of the literature discloses that the idea of using lasers for sealing plastic-to-plastic goes all the way back to the 1960s, when lasers were first being considered for industrial applications. More recent literature indicates that the concept of using a laser to seal glass lids to LCP molded packages is a

known art and apparently in the public domain—free of patent restrictions. A Kodak patent describes an LCP package for CCD where the glass lid can be bonded "cover glass 16 would be attached to the top open area of ring frame 14 by any of numerous *conventional means including* but not limited to: adhesive; heat sealing; ultrasonic welding; or *laser welding*."[22] The inventor did not claim laser sealing to LCP packaging, but rather disclosed it as being well known. A glass lid was sealed to a molded LCP package that had an insert-molded flexible circuit as the interface, a design that could have some applications for MOEMS. Figure 4.16 shows the concept. Others also refer to the use of laser energy through glass as a lid seal method.[23]

It was found that glass sealed well to LCP, provided that there was absorption and even a small amount of black colorant efficiently absorbed energy. LCP and other plastic are typically colored black with dispersed carbon black that is commercially available as resin pellet concentrate that can be blended with clear resin. Most plastic packages are black and readily absorb energy. We were able to seal glass to our packages, and to test caps, and obtain high adhesion. The glass seals passed both the gross leak test and helium fine leak test. The fine leak test was performed by an outside lab that reported no detectable leaks for 25 samples within the limit of their test sensitivity of 1×10^{-9} atm·cm^3/s He. One more caution is that passing the helium fine leak test is NO proof of hermeticity or ability to pass MIL STD testing. Power, beam size, and traverse rate were varied over a wide range with excellent bonding. The results suggest that a near infrared laser is a practical means of sealing glass lids to molded LCP.

Tests were also run on LCP film and sheet material used as a lid seal. The lid material should have no *infrared* (IR) absorber since heating should occur at the interface. Lid thickness ranged from 2 to 25 mils. While a 2-mil-thick film is readily bonded to our LCD package, the material is so thin that it can fail during *joint electron device engineering council* (JEDEC) testing. The heating to simulate soldering conditions can generate enough internal pressure to delaminate the thin material by allowing peeling to occur. But materials of 4 mils and greater do not show this failure, although bulging was observed during heating at 4 mils thick. The maximum thickness limit, at least for our laser is

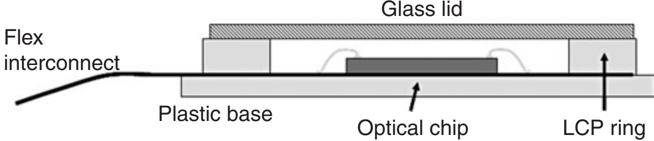


Figure 4.16 LCP-flex package with glass lid.[8]

about 25 mils. Absorption and scattering appear to reduce the beam energy to a level where sealing is inadequate. Figure 4.17 shows possible laser sealing pathways. While laser sealing offers interesting possibilities, this is not a common process for package assembly and should be considered a custom method.

Thermoplastics can be interposed between a nonplastic package and glass as an adhesive material. Laser energy will pass through the glass and melt the plastic if absorbed and converted to heat. Some of the dark-colored ceramic packages will absorb IR and *near infrared* (NIR) to melt the plastic adhesive spacer and no absorber is needed in the plastic. LCP should definitely be evaluated as a near-hermetic adhesive for glass-to-ceramic. Since barrier properties are better than UV-epoxies that are apparently almost good enough, LCP may meet the requirements. The film could be die cut or laser machined into frames that could be tacked onto lids.

4.9.4 Ultrasonic sealing

Ultrasonic energy has been used to bond metals, plastics, and other materials for a long time. One or more of the materials must be able to melt or diffuse into another to create a bond. Wire bonding is just one example of how fast the process can be run. Ultrasonic welding involves

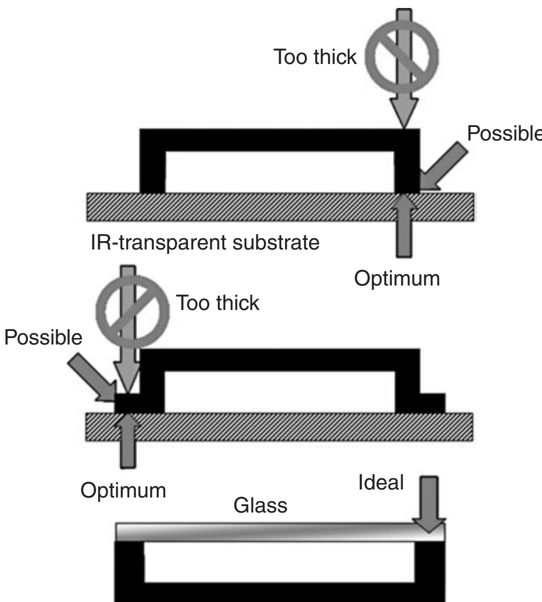


Figure 4.17 Laser sealing pathways.

the use of high frequencies beyond the audible range to soften, or melt the thermoplastics, or metals at the bond site. The vibrational energy is transmitted through a booster that increases the amplitude of the wave. The ultrasound waves are then transmitted to the horn—an acoustic tool—that transfers the vibratory energy directly to the parts being assembled. The horn also applies the welding pressure required for bonding. The vibrations are transmitted through the work pieces to the joint area where the mechanical energy is converted to thermal energy through friction that will soften or melt the materials together.

A lid can be joined to the package body by applying some pressure and then activating ultrasonic vibrations: typical frequencies are 20, 30, or 40 kHz. Many ultrasonic welding machines operate at 20 kHz or greater, since this is above the highest frequency detected by the human ear. The weld quality is governed by the design of the equipment, design of the components, the properties of the material to be bonded, and the energy process. Ultrasonic welding of parts often takes less than 1 s and is easily automated. The four main components of a welding machine are (1) power supply, (2) converter, (3) amplitude-modifying device (commonly called a booster), and (4) acoustic tool known as the horn or *sonotrode*. The power supply converts 50- to 60-Hz electrical current to a high-frequency ac current at 20, 30, or 40 kHz. To power the converter that can be piezoelectric material sandwiched between two metal electrodes, the converter transforms the electrical energy into mechanical vibratory energy at specified ultrasonic frequencies. The process is energy efficient, provides high productivity at low cost, and is easily automated. Some LCP molded packages and lids for MEMS are thought to be ultrasonically welded.

4.9.5 Direct heat bonding

A heated tool, sometimes called a thermode, is pressed against the lid to directly transfer thermal energy. The shape can be a “picture frame” that impinges the edges of the lead or a solid block. Some units can heat up in less than 1 sec and have very well-direct energy for high efficiency and productivity.

4.9.6 RF sealing/welding

Radio frequency (RF) welding, dielectric welding, or high-frequency welding, is an energy localized process for fusing materials together by applying RF energy that is transformed to heat at the bonding site. The process is useful for joining polymers that have strong dipoles, such as *polyvinyl chloride* (PVC), polyurethanes, and polyamides. The high-intensity alternating RF cause the dipoles (polar groups) to orient with

the electric field. These dipole molecules attempt to alternate with the changing field polarity that is changing too rapidly. The diploes convert some of the field energy into heat thus creating a weld. In the United States, the FCC has established permissible frequencies to prevent unnecessary interference with other radio systems. The most common RF welding frequency in the United States is 27.12 MHz, but frequencies can vary depending on the country. The high-intensity field is applied to the polymer by electrodes that contact opposite sides of the plastic material. Since field intensity decreases with distance, this process is normally most useful when the electrodes are close together as with polymer films. The need for polar molecules and the electrode configuration limits the use and this may not be an ideal process for packaging.

4.9.7 Electric welding

Fully automatic lid welders are available that can even produce vacuum- or gas-filled metal packages. Various means of applying electrical power to the lid can be used—clamping, rollers, parallel seam rollers, and so on.

4.9.8 Mechanical locking

Mechanical locking ideas have been tried but do not produce hermetic seals. Plastic parts can be made that snap fit, and metals can be crimped. A combination of snapfit and seal may have value, however.

4.9.9 Soldering

Solders have long been used to seal metal lids to metal packages, and glass and ceramic can be metallized to be made solderable. Solder can be coated onto the lid or a preform can be punched to the size of the lid perimeter. Many heating processes are used from simple ovens to lasers.

4.9.10 Brazing

Brazing is akin to solder, since a joining metal is used to form a joint between the lid and package, but the bonding temperature is higher. Brazing is defined as metallurgical joining process above but is usually in the 440 to 593°C. Both soldering and brazing involve wetting the metallic surfaces to be joined with a molten brazing alloy, which spreads by capillary action and then upon cooling, forms a strong metallurgical joint. Brazing is favored for applications requiring stronger joints and/or temperature resistance. Gold-tin melting at 280°C is a common lid brazing material.

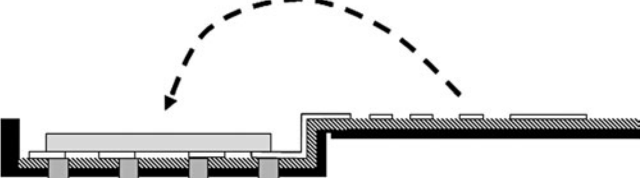


Figure 4.18 Molded package-lid.

4.9.11 Hinged-to-package lids

The plastic molding process and the properties of many thermoplastic resins allow plastic hinges to be fabricated. One popular design is for container caps that everyone is probably familiar with. The same principle can be used for cavity packages. A plastic lid can be molded along with the package, so that lidding involves folding the hinged lid and sealing. Depending on the seal required, a mechanical snap lock design can be used without sealing. But it is possible to add another important feature by use of the hinge. A flexible circuit can be insert-molded so that signals can be routed to the lid. This will allow components to be placed. The package and lid can be positioned, so that chips can be assembled to the package base and lid, followed by lid closure as shown in Fig. 4.18. But there is one more feature that can be added and that is pass-through connections to the top of the lid. Such a design would allow packages to be stacked as shown in Fig. 4.19.

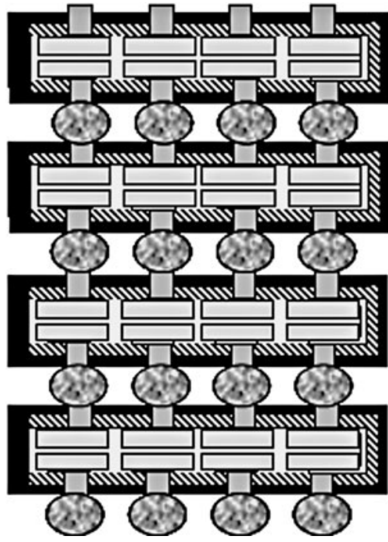


Figure 4.19 Stackable package-lid.

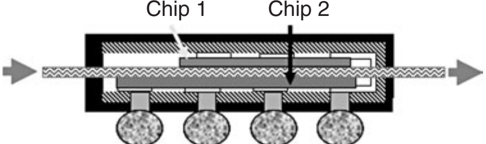


Figure 4.20 Spectrophotometer package.

There could be many possible uses for a multichip stackable package design for MEMS devices. But the base and lid chip assembly could be useful for some MEMS and optoelectronic systems, since the chips can be positioned face-to-face. For example, a laser or LED (or several) could be used as the light source while opposing photodetectors could be the receivers. A transparent sample transfer tube could be interposed between the two types of devices to create a spectrophotometer. The package now becomes the sampling head of a spectrophotometer that could be used as a disposable unit or a real time monitoring system with several units feeding information to a central analyzer. Figure 4.20 shows this concept.

4.10 Antistiction Processes

Stiction results from short-range atomic and molecular attractive forces especially when the materials have high surface energy. Moisture absorption exacerbates the problem. Ideal antistiction treatments should have strong adhesion to the MEMS structure, low surface energy, and be hydrophobic. Two chemical classes that meet these dual requirements are silicones and fluorochemicals that have long been used for waterproofing and stain repellency. The application thickness could be as low as a single molecular layer, and this could be accomplished with liquids or vapors that have an affinity for the substrate. Very thin layers of solids—especially polymers—can also be effective. But, the thickness must be controllable so that the layer remains thin enough and does not interfere with mechanical action. The material must not interfere with die attach or first-level assembly if applied at wafer-level. This could require a means of preventing a dielectric material from covering bond pads or adding a step to remove material unless the application takes place after bonding. Some processes have applied antistiction coatings just before lid seal. One process, apparently once used for accelerometers, involves sealing the lid that has a prefabricated vent hole, adding silicone fluid, heating the package to vaporize the fluid, and finally plugging the hole.

The earliest materials were vaporizable silicone fluids that were added after die attach and wire bonding. One method, used early on by ADI

for accelerometers was the addition of silicone fluid into a tiny opening in the otherwise sealed package. The company now applies antistiction films at wafer-level to a thickness of only 0.2 nm. Heat was used to vaporize the fluid so that it coated the MEMS surface areas. The final step was to seal the hole.[24] Texas Instruments uses a fluorinated fatty acid *self-assembled monolayer* (SAM) on the aluminum oxide surface in their DLP,[25] while ADI coats the surfaces of their inertia sensors using thermal evaporation of silicone polymeric materials at the packaging stage after the device is completely released. Another much advocated approach is the formation of SAMs on the oxide terminated surface, but the difficulty of this chemistry and the poor reproducibility put significant limitations on its practical usage.

Fluorinated parylene could also be useful as a coating for antistiction and antiwear. Parylene conformal coating technology, originally developed by Union Carbide, has been in commercial use for several decades. Parylene (poly-para-xylylene) is a high-temperature polymer film applied to substrates in a vacuum chamber by means of a gas phase polymerization that provides unusual electrical and environmental performance. This class of polymer has a long and successful history in a variety of applications, especially those involving the protection of electronic devices and circuitry. CVD is used to form an insulating thermoplastic coating with a high degree of chemical inertness, absence of pinholes, and perfect conformity to the topography of the surface applied. Coefficients of friction range from 0.25 to 0.33, so that the lubricity is close to that of Teflon. Table 4.2 summarizes the attributes of value to MEMS.

The parylene coating material is a granular white powder that is used in a specialized vacuum coating chamber. Parylenes are applied in a three-stage vacuum deposition process: (1) vaporization of the dimer at 150°C and 1.0 torr, (2) molecular cleavage or pyrolysis to a reactive monomer (dimer) at about 680°C/0.5 torr, and (3) polymerization

TABLE 4.2 Parylene Attributes

Attribute	MEMS	MOEMS
Stress-free coatings	Yes	yes
Thin contiguous film without pinholes	Yes	yes
Inert	Yes	yes
Even coating of sides and edges	Yes	yes
Hydrophobic	Yes	yes
Low surface energy, especially fluorinated Nova HT	Yes	yes
High temp capability up to 500°C	Yes	yes
Low k down to 2.28	Yes	
Optically clear, UV resistant		yes

of the thermally stable, kinetically unstable dimer on the cooler substrate at 0.1 torr. The reactive gas polymerizes spontaneously on the surface of coated objects that are at ambient temperature, with no stresses induced initially or subsequently. There are no cure related hydraulic or liquid surface tension forces in the process. The mean free path is only about 0.1 cm so that sides and small openings are coated. A typical rate of 0.2 μm or less provides precise thickness control. Polymerization occurs in crevices, under devices, and on exposed surfaces at about the same rate to give a very uniform film. The coating thickness can be as low as 100 A.

Nova HT shares the unique properties of the other parylenes, but offers properties that should be ideal for antistiction. The film is deposited in a molecule-by-molecule polymer process, with no cure related stress that can occur with liquid polymers. There is no liquid phase, no hydraulic forces, and the coating conforms to substrate features rather than pooling or bridging in the manner of conventional liquid coatings. Free molecular dispersion of the monomer results in the development of an overlying film on all exposed surfaces, with equal thickness on inside and outside corners, flat surfaces, and in crevices. Parylene can effectively penetrate inside surfaces through small openings. The newer Nova HT has a crystalline melting point of above 500°C, which is at least 250°C higher than the recommended continuous exposure level for the conventional parylenes. Nova HT can be used for applications that require exposure to lasers and high intensity lamps such as MOEMS with its improved UV resistance. It is particularly resistant to yellowing and physical degradation under such conditions.

This advanced coating has all of the useful properties of traditional parylenes including resistance to solvents, moisture, gases and other contaminants, high dielectric strength in very thin layers, and favorable physical and electrical properties. Nova HT polymer is the fluorinated version of Parylene N. Its superior properties are due in part to the integration of fluorine into the parylene lattice, which results in improved polymer stability. Nova HT has its origin in *specialty coating systems* (SCS) Parylene VIP AF-4 developed as an interlayer dielectric for the next generation of very high-speed and fine-pitch integrated circuits. Its especially low dielectric constant minimizes the interlayer capacitance of ICs, and enhances operating speed by minimizing both power consumption and cross-talk. Like Parylene VIP AF-4, new Nova HT has a dielectric constant of only 2.28, and a crystalline melting point above 500°C. Nova HT film is applied to substrates in a similar vacuum process to conventional parylenes. However, the required temperatures, pressures, dwell times, product preparation, and fixturing are unique for this new material, and involve a proprietary process that has been developed by SCS.

4.11 In-Process Handling

MEMS and MOEMS devices are very fragile and extremely sensitive to contamination at some stages of packaging. The critical point is just after release and just before package enclosure. Some schemes apply a protective cap just after the release step while the product is still in the protective environment of the MEMS fab. All in-process handling steps need to take into account the fragility and sensitivity of devices, and each product will have different sensitivities and process requirements.

4.12 Applying In-Package Additives

Several types of additives are used for MEMS and MOEMS devices that may be added as part of packaging or just before. Materials can be grouped into two main categories—atmosphere control and device treatment. Getters are the most important atmosphere control or regulating materials. Materials can be applied to the chip, the package body, or the lid.

4.12.1 Getters application processes

Getters are selective scavengers, or attractors, designed to capture and "kill" the undesirable substances. Their material aspects are covered in detail in Chap. 5. The list includes getters for several gases, liquids, and solids. Important gas getters include oxygen and hydrogen, both of which are found inside the hermetic package and known to be harmful. The most important liquid getter targets water although as a vapor under the high vacuum conditions. Some of the moisture getters also trap ammonia, sulfur dioxide, and other harmful species that can be found in packages. Getters for solids are of general purpose and capture small particles regardless of the composition. While other getters can be designed, these are the important types for both high reliability electronics and MEMS. The Texas Instruments DLP package, for example, uses getters. Moisture and particle getters are especially important for MOEMS devices and can be combined into a single and multipurpose material.

Getters are most commonly applied as solid films that may have a built-in adhesive quality. The solid type often made with a plastic binder, can be cut to size and attached to the inside of a cavity package. Some require the addition of a special low outgas adhesive, and most have a baking step to cure the adhesive and to remove residual volatiles. There are paste forms of getters that can be coated onto lids, or applied to the lid, or package housing by needle dispensing. These products have a specific curing or drying step.

4.12.2 Lubricant application

Researchers in the MEMS reliability area have proposed that lubricants can be added to the MEMS package to reduce wear, friction, and stiction. Materials can be applied as solids that release vapors and the application methods are similar to those for getters. Some materials are liquids that are applied as a microdrop to the interior of the package before lid seal. As mentioned earlier, with antistiction agents, a lubricant can be added to an opening in the lid and then the hole is plugged.

4.13 Equipment

More recently, some semiconductor equipment makers have designed systems specifically for MEMS, including back-end operations. EV Group of Austria appears to have worked harder designing and building MEMS equipment than others, although they are not alone. EV Group offers wire bonders, aligners, coaters, cleaning machines, and wafer bonders with MEMS in mind. AML also offers bonders that are claimed to be configured for MEMS. Some of the optoelectronic assembly builders have also skewed their equipment toward MEMS as the *optoelectronics* (OE) market struggled.

4.14 Testing

Package reliability testing often follows the MIL STD 883 methods that deal with hermetic packages.

4.15 Reliability

According to Dr. Stuart Brown, who has studied MEMS failure extensively, there are many more unknowns than established facts when it comes to MEMS reliability.[26] Dr. Brown now is a principal engineer and director of Exponent's Natick, Massachusetts. Brown points out that the reliability of these MEMS devices can now match the macrotechnologies that they replace. For example, airbag accelerometer lifetimes exceed those of both the distributed sensors and wiring harnesses used previously, and will also easily exceed vehicle life. In many cases, the ability to reduce hand assembly and to integrate sensing and electronics translates to immediate improvements in product mean times before failure.

But many other applications are more challenging, both for device performance and the knowledge of the physical phenomena governing reliability. The amount of reliability test data is sparse compared to equivalents in the macromechanical world. Reliability can even constrain commercialization and this has been an issue with contact devices

such as RF switches. In the macroscopic world of mechanical switches and relays, product lifetimes are frequently specified in millions of actuation cycles. In the microscopic world of MEMS, RF switches are being fabricated and prototyped for projected actuation lifetimes that can exceed 100 billion cycles—easily pushing four orders of magnitude in expected reliability. Reduced insertion losses and excellent isolation make microswitches obvious replacements for standard solid state switching devices that are very reliable, but include certain compromises in electronic performance. Opportunities for replacement of solid state devices include switches, phase shifters, and tunable filters for both commercial and defense applications. The low insertion losses and better isolation translate to lower power consumption, longer battery life, and reduced distortion. The advantages are clear, and many organizations are pursuing different designs.

Our concern here is the effect of packaging on reliability, however. Contamination and the ability to keep the level low are of high concern. The package enclosure not only determines if contamination will pass into the package and gain access to the device, but also what package-generated materials will access the MEMS device. So it is important to understand the effect of contamination of reliability. However, the contamination effects will be somewhat product dependent.

4.15.1 Contamination effects

MEMS small size and the very high ratio of area to mass exacerbate the importance of contamination. Contamination affects all MEMS mechanisms, but some more than others. Rapidly moving elements such as resonators are especially sensitive, as are switches that make contact (ohmic switches) compared to contactless (capacitative). Consider a cantilever resonator that is 1 μm long, 50 nm wide, and 20 nm high. Materials such as water will have damping effects. A cantilever's resonator at a frequency of 30 mHz will shift downward by about 0.6 percent, if a single layer of water is absorbed on the surface. Such a shift will typically move the resonator out of spec for many applications. If the MEMS resonator is reduced by a factor of ten in all dimensions, then a single layer of water would change the natural frequency by 6 percent. Hermeticity and contamination remain a challenge for many but not all devices. The DLP MOEMS device with 1.3 million micromirrors and supporting structures is also very sensitive to contamination, especially particles. One small piece of silica will jamb the 16-μm square mirror to "kill" a pixel. Not only must the package for such contamination-sensitive-high-reliability devices be hermetic, getters are usually necessary to reduce the hazards from dislodged or wear particles that can be released from inside the package. On the other hand, an ink-jet chip

will easily tolerate moisture, since it uses an aqueous ink external particles are not generally a hazard.

4.16 Selecting the Right MEMS/MOEMS Package and Materials

By now it should be clear that MEMS devices have diverse and specific needs and that there can be no standard generic package. The material choice will depend on the level of hermeticity, and most importantly, the level of moisture exclusion required. But this may also depend on the amount of passivation rendered to the chip by prepackaging processes, including capping. Plastic without a special barrier coating will not give more than modest hermeticity and the MIL STD 883 test for hermeticity and moisture resistance will not be passed even with the best polymers. However, capped MEMS devices can and are packaged in both premolded plastic cavity packages and postmolded encapsulation. It is also possible to add hydrophobic silicone gels to the interconnect region in plastic cavity packages to prevent metal corrosion where the package cannot exclude moisture.

Ceramic package can readily pass hermeticity tests, but the cost will be four to five times higher than the lowest cost premolded cavity package and about ten times higher than the lowest cost over-molded *quad flat no-lead* (QFN) package. Ceramic is a good choice when hermeticity must be maintained at a high level. Custom metal packages should be avoided unless there is a compelling reason to use them. The exception would be a metal can type, like the *transistor outline* (TO) that can be cost-effective but has a limiting number of I/Os and is not easily modified from the standard formats. A custom metal package can be 100 to 1000 times more expensive than the lowest cost plastic overmolded package typified by the QFN. Chapter 5 goes into considerable details on materials.

4.16.1 The process cost overkill

When the costs just provided in the previous section are considered, it is easily seen that overspecifying the package can be prohibitively costly. For example, let us say that a metal machine package was selected at a cost of $5.00 because the MEMS device required very low moisture content. One would need to consider a ceramic package that could cost $0.50 to $1.00. But even if the ceramic package was found to meet requirements, plastic should still be investigated. But since moisture will slowly transfer through the best molding plastics, this material would not seem to be an option. However, could a barrier coat be added at reasonable costs? At the time of this writing, no barrier system has been

established for molded plastics, although the possibility still remains. So could the device be passivated? The most proven process is capping, so we would need to determine if the MEMS device could be capped. If so, capping could at a small amount or even a modest cost. Let's say that capping added $0.10, then the cost of a capped and overmolded package could be as low as $0.15. But if a cavity style package was needed, the cost could still be as low as $0.20 to $0.25. Plastic package would be the best option.

The same analysis should be performed on a MOEMS device. If high hermeticity was needed, could the device be capped with a transparent material? If the answer is yes, then a plastic package could be used. It might be possible to overmold up against the glass cap, but a safer option would be to use a premolded cavity package with a transparent lid. A glass or transparent lid could be used without a significant cost addition. Plastic again would be the most cost-effective option.

4.17 Conclusions and Summary

The process set is clearly the most important consideration for cost, performance, and design flexibility. However, materials strongly determine, and often limit, the available processes. Thermoplastic resins offer the most versatility in terms of design and manufacturing, but plastics also provide the weakest barrier to gases and vapors. Plastics should always be considered for all medium and high volume packaging applications. Plastics, especially thermoplastics, can be shaped into the most complex and intricate configurations, but they should not be used for devices that require full hermeticity or are sensitive to moisture. But before moving to the next cost level of materials, chip passivation, especially capping, should be explored.

Ceramics also offer versatility but at a five to ten times higher cost than plastics. However, ceramics provide features and properties not found in plastics. Key features include full hermeticity, very high temperature stability, low CTE values, and high thermal conductivity. Ceramics can also be molded into cavity packages.

Metals, although one of the oldest materials worked by man have not kept pace in terms of processes suitable for low-cost packaging. Perhaps the market is not large enough to warrant development. Metal enclosures also have the added problem of being electrically conductive. This means that there will always be the added steps to create electrical pass-through points. Although there has been substantial progress in metal-shaping process for the macro and nanoscale levels, these methods have not been applied to packaging.

Based on material properties and available processes, ceramic, and plastics are the preferred dielectric enclosure materials for MEMS and

MOEMS. Ceramics almost always can provide the solutions for the technical needs, but not always at the cost targets needed for many markets. Plastic packaging technology has achieved heroic cost reductions in the past few years to a level where an electronic chip can be packaged, including labor and materials, for less than a nickel in a noncavity configuration. But even plastic cavity packages that have complex precision features and dimensions can be produced at a slightly higher cost. But neither provides hermeticity at this point of time. Advancements in barrier coatings and wafer-level passivation could make plastics the dominant MEMS package in the future.

References

1. Russick, E. M., et al., "Supercritical Carbon Dioxide Extraction of Solvent from Micromachined Structures," *Symp. Series*, Vol. 670, pp. 255–269, 1997.
2. Roberts, Jr., et al., "Method for Separating Circuit Dies from a Wafer," U.S. Patent 5,362,681, November 8, 1994.
3. Le, M., et al., "Optical Membrane Singulation Process Utilizing Backside and Frontside Protective Coating During Die Saw," U.S. Patent 6,420,206, July 16, 2002.
4. Mignardi, M. A., "From ICs to DMDs," *TI Tech. J.*, pp. 56–63, July–September 1998.
5. Sahakian, V., "Integrated Circuit Chip Sealing Assembly," U.S. Patent 4,907,065, March 6, 1990.
6. Yamamoto, K., et al., "Hermetic Sealing of Wafer Scale Integrated Wafer," U.S. Patent 5,150,196, September 22, 1992.
7. Adams, V., et al., "Semiconductor Wafer Level Package," U.S. Patent 5,323,051, June 21, 1992.
8. Roberts, Jr. C., et al., "Method for Separating Circuit Dies from a Wafer," U.S. Patent 5,362,681, November 8, 1994.
9. Spooner, T., et al., "Method and Device for Protecting Micro Electromechanical System Structures During Dicing of a Wafer," U.S. Patent 6,555,417, April 29, 2003.
10. Felton, L., "Method and Device for Protecting Micro Electromechanical Systems Structures During Dicing of a Wafer," U.S. Patent 6,759,273, July 6, 2004.
11. Barmatz, et al., "Microwave Bonding of Thin Film Metal Coated Substrates," U.S. Patent 6,809,305, October 26, 2004.
12. Harris, R., et al., "Method for Fabricating an Isolated Microelectromechanical System (MEMS) Device Incorporating a Wafer Level," U.S. Patent 6,768,628, July 27, 2004.
13. Brady, F., "Wafer-Level Through-Wafer Packaging Process for MEMS and MEMS Package Produced Thereby," U.S. Patent 6,660,564, December 9, 2003.
14. Martin, J., "Covers for Micromechanical Sensors and Other Semiconductor Devices," U.S. Patent 5,610,431, March 11, 1997.
15. Gilleo, K., *The Handbook of Flexible Circuits*, Van Nostrand Rienhold, New York, 1992.
16. Steinfield, S., et al., "Stable Substrate Structure for a Wide Swath Nozzle Array in a High Resolution Inkjet Printer," U.S. Patent 6,332,677, December 25, 2001.
17. Jacobs. J., and J. Malone, "Suitability of an Epoxy Seal for a MEMS Package," *Proceedings of the 33rd International Symposium on Microelectronics*, Boston, MA, September 20–22, 2000, pp. 586–591.
18. Gilleo, K., and G. Pham-Van-Diep, "Encapsulation Materials, Processes & Equipment," *Adv. Packaging*, Vol. 3, No 10, pp. 38, 40, 41–42, October 2004.
19. Gilleo, K., et al., "Plastic Hermetic Packages for MEMS, MOEMS & Optoelectronic Devices?" *Proceedings APEX*, Anaheim, CA, March 31, 2003.
20. Gilleo, K., et al., "Low Ball BGA: A New Concept in Thermoplastic Packaging," *Semicon West*, San Jose, CA, July 13–17, 2004.
21. Gilleo, K., et al., "The Time is Right for Injection-Molded Packages" *SMTA-International*, Chicago, IL, September 27, 2004.

22. Wetzel, and Keith, "Low Cost CCD Packaging," U.S. Patent 6,011,294, April 8, 1996.
23. Rentsch, A., et al., "Use of Alternative Materials for Packaging of Sensors and MCMS," *MicroMaterials Conference (MicroMat 2000) Proceedings*, Berlin, April 17–19, 2000.
24. Martin, J., and Y. Zhao, "Micromachined Devices Packaged to Reduce Stiction," U.S. Patent 5,694,740, December 9, 1997.
25. Hornbeck, L., "Low surface energy passivation layer for micromechanical devices," U.S. Patent 5602671, February 11, 1997.
26. Brown, S., "A Little Knowledge," *Mech. Eng.*, October 2003.

This page intentionally left blank

Chapter

5

MEMS Packaging Materials

Materials are the key to processes, performance, and cost. Throughout the millennia, some materials have been highly valued for beauty, others for their rarity, and still others because of alleged magical properties. Even today, materials can determine the power and rank of nations in the world order. While natural resources have brought wealth and a certain measure of power to nations, it is the synthesized and manufactured materials that create true wealth and confer power on nations, companies, and people. Electronics, probably to a greater degree than any industry, has created great prosperity and extraordinary technology by the brilliant manipulation of common materials into those that are exotic, with properties not found in nature. Sand and common metals are turned into chips worth millions of times more than the raw materials because they contain hundreds of millions of nanoscale parts that can do the mental tasks of thousands of people in a fraction of the time. Component packaging also relies on manufactured materials with properties that have been crafted and tuned over decades, and also from well-known elements like aluminum, carbon, copper, nickel, oxygen, and gold. It is the material that sets the limits on performance and ultimately defines the cost of the product and the markets that are available. We will look at the packaging materials with emphasis on those that are suited for MEMS and MOEMS.

5.1 The Process Determines the Materials

While a given process will determine the range of materials that can be used, the reverse is also true. We could decide what processes were best suited for packaging and that would limit the materials. But materials also determine package performance, at least from the hermeticity criterion, and this makes materials a good starting point once the package requirements

Copyright © 2005 by The McGraw-Hill Companies, Inc. Click here for terms of use.

are established. When we talk about metal, ceramic, or plastic packages, we are referring to them as enclosures or encapsulants. In all cases, the electrical interconnect is metal or metal-based and it is understood that plastic and ceramic packages contain metal, although the form can be different for each material class, but not necessarily.

We can generally select materials for packages from the broad categories of metals, inorganics, and organics. Metals for packaging enclosures include aluminum (Al), chromium (Cr), cobalt (Co), copper (Cu), gold (Au), iron (Fe), nickel (Ni), silver (Ag), and special alloys such as low expansion materials like Kovar. Electrical interconnects use aluminum (Al), Beryllium (Be), copper (Cu), gold (Au), tin (Sn), lead (Pb) (being phased out), nickel, palladium (Pd), platinum (Pt), tungsten (W), silver, and a few others. Inorganic packaging materials include ceramics [based on compounds of Al, Be, B, Si (silicon), and a few others], glasses, silicon, silicon dioxide (SiO_2), and some that might be classified as minerals. Organics are primarily polymers that can be divided into the two main classes of *thermosets* and *thermoplastics*. While most plastics are based on the chemical elements, carbon (C), hydrogen (H), and oxygen (O), we may need to add bromine (Br), chlorine (Cl), fluorine (F), nitrogen (N), phosphorus (P), boron (B), and sulfur (S) to the list. However, polymer backbones are generally made up of a short list of elements—carbon, oxygen, hydrogen, chlorine, nitrogen, and sulfur. The last two elements, S and N, often impart low flammability and high temperature performance. Fillers added to the polymers are mostly based on silica, but aluminum nitride (AlN) and a few others can be used.

5.1.1 Electrically conductive materials—interconnects

Aluminum has long been the favored electrical conductor for integrated circuits, although there has been a steady transition to copper over the past several years. Aluminum metal is easy to vacuum deposit but readily forms a strong insulative oxide that can be a help or a hindrance. But aluminum's properties make it a relatively poor choice for packaging, especially the formation of a tough insulative oxide that makes soldering impractical. The short-lived replacement of copper home-wiring with aluminum wiring several decades ago proved a disaster because of the growth of aluminum oxide that could "open" junctions. Aluminum is only a moderately good electrical conductor, and this is one of the reasons for the changeover to copper by the semiconductor industry. Table 5.1 compares metal electrical conductivity values.

The preferred package electrical conductor is presently copper, which is abundant, relatively cheap, easily fabricated into patterns, readily soldered, and generally a low hazard. The metal has been used for several millennia; and an entire millennium, the Bronze Age, was named after the

TABLE 5.1 Metals Electrical Conductivity

Metal	Relative electrical conductivity*
Aluminum	59
Copper; drawn wire	89.5
Copper; annealed	100
Gold	65
Nickel	12–16
Silver	106
Tin	13

International Metals News; AAM.com
*At 20°C based on copper as 100.

copper-tin alloy. Copper has been the workhorse electrical conduit for the electric power grid, premise wiring, automotive wiring, printed circuit boards, and electronic packaging; and it will remain the *de facto* standard into the foreseeable future. Copper is compatible with many metals and its ability to dissolve some alloys like tin, makes it easy to solder which requires metallic solubility. This high solubility also requires that barrier coatings be added, like nickel, to prevent metals like gold from diffusing into copper. Copper is unlikely to be replaced by any other metal as a packaging conductor, but organic conductors, perhaps something based on carbon nanotube structures, could become the conductor of the future. See Chap. 6 for more on nanotechnology.

A few other metals are used for package substrate conductors, but not nearly to the extent of copper. Silver, especially silver-palladium (Ag-Pd), is commonly used with ceramic packaging. Silver is actually a better conductor than copper as shown in Table 5.1, but its popularity in ceramic circuitry and packaging platforms, and also in low-cost flexible circuitry is mostly because of other properties, like electrical conductivity of silver oxide and ease of forming powder and flake. These silver properties enable conductive inks and adhesives to be made from silver powder and flake. These silver products form stable conductor traces and junctions since no insulative oxide coating forms. The mechanical and chemical properties permit silver powder and flake to be manufactured with optimum morphology. Unfortunately for copper, its particles quickly form insulative surface oxide and copper-based inks must therefore be sintered under reducing atmospheres while silver ink can be processed in air. Copper inks with oxide inhibitors and special surface coatings have been developed over the past 30 or more years, but none have proved to work as well as silver-based inks, at least not yet.

Polymer thick film (PTF)[1] circuits can be made with silver ink that is hardened at 100 to 150°C, while stable and truly practical PTF copper inks

have eluded researchers for decades. PTF inks have not found much use in packaging unless one considers *radio frequency identification* (RFID) tags as a package; a chip that is connected to a system by wireless. *Ceramic thick film* (CTF) technology is widely used in ceramic packaging, however. Silver-bearing compositions are generally used. But since silver is so chemically active, it can form compounds that hydrolyze and ionize to eventually cause short-out problems when silver electromigration (electroplating type of phenomenon) occurs. This tendency can be greatly reduced by alloying silver with approximately 20 percent palladium. Ag-Pd cermet (ceramic metal) inks are common for ceramic circuits and package platforms. Cermet inks are Ag-Pd composition that are commercially available in ratio from 3:1 to 12:1, and are fired at a temperature range of 800 to nearly 1000°C.

Copper CTF inks have advanced over the past two decades and some ceramic package platforms use copper inks. "Snapstrate" (precut for mechanical singulation) copper BGA platforms that have low CTE values are commercially available. Multilayer products are available with solid or filled copper vias for high density. *Low temperature cofired* ceramic (LTCC) technology is becoming increasingly popular for ceramic packaging. It is also possible to plate pure copper onto ceramic and etch a circuit pattern.

5.1.2 Surface finishes for metals

Copper is also used on virtually all organic substrate and is the conductor of choice. Copper patterns can be formed by etching away unwanted copper using the common subtractive process, or by fully additive and semiadditive processes that deposit copper by plating. The result in all cases is a rather pure copper conductor that quickly oxidizes or tarnishes, making soldering more difficult and wire bonding nearly impossible. Bare copper is therefore finished, or overplated with more suitable metals or even organic protectors. In most cases where a metal finish will be applied, nickel is first applied by plating. This is the barrier coating needed for gold or palladium to prevent these metals from diffusing into the copper. Gold and copper are very compatible and if gold is plated directly onto copper, the metal will seem to disappear as the gold atoms diffuse and are distributed into the copper structure. Nickel, although solderable, may be plated over with a thin gold coating to prevent oxidation. Simple gold immersion plating, a double displacement chemical reaction, will deposit a thin gold coating onto any exposed nickel without the use of electric current. Nickel dissolves in the ionic gold salt plating solution while gold metal is deposited onto nickel. The reaction continues until no more exposed nickel is available, making this a self-limiting process. The thin gold is suitable for flip chip assembly and general soldering, but not for wire bonding. Wire bonding requires a thicker deposit, and this must be

done by electroless or electrolytic plating. Silver immersion finishes, especially types with migration inhibitors, are becoming more popular. The immersion silver is not suitable for gold wire bonding but may be adequate for less-common aluminum wedge bonding. *Organic solderability preservatives* (OSP) may also be applied to copper but these complexing agents do not have the longevity of plating.

5.1.3 Enclosure materials

Glass was the original hermetic enclosure material for vacuum discharge tubes; Geissler (1850s) and Crookes (1870s) devices; gas discharge lights; neon displays; *cathode ray tubes* (CRTs); lighting devices; and fluorescent and electronic vacuum tubes. Many glass "envelopes" are still used today. Packaging materials for electronics have been mostly replaced by technical ceramics that are stronger, have better thermal characteristics, and are easier to fabricate. But we need to be cautious with definitions for "glass" and "ceramic." Glass is actually a ceramic material, but do not include it in the list of ceramics. Common glass is mostly silicon dioxide (SiO_2) and has a similar chemical composition to that of materials we call ceramics, but the main difference is in the microstructure. Glass is amorphous while popular ceramics are crystalline. Glass will slowly creep, or be slow at ambient, and an old window will be thicker at the base than the top because of creep.

The term *ceramic* covers such a vast array of materials that making a single definition is neither very practical nor very useful. Some have suggested that the word ceramic should be divided into the traditional (clay products, silicate glass, and cement) and advanced, or technical ceramics (carbides; SiC, pure oxides; Al_2O_3, nitrides; Si_3N_4, AlN, and nonsilicate glasses). Ceramics are nonmetallic, nonelectrically conductive, inorganic chemical compounds composed of metallic and nonmetallic elements such as aluminum and oxygen; alumina (Al_2O_3), calcium and oxygen (calcia–CaO), and silicon and nitrogen; silicon nitride (Si_3N_4), that are typically crystalline. Most ceramics are made up of two and sometimes three chemical elements, but they can be much more complex. Ceramic materials derive their strength from both covalent and ionic chemical bonds that tends to make them very strong, but also brittle. The ceramic microstructure can be entirely glassy (amorphous glasses only), entirely crystalline, or a combination of both crystalline and glassy. The atomic structure influences the chemical, physical, thermal, electrical, magnetic, and optical properties. The microstructure also affects these properties and determines many of the mechanical properties. Alumina is the most common ceramic for electronic packaging.

Ceramic materials are some of the most common enclosure materials for MEMS. Three large Japanese companies—Kyocera, NTK, and Sumitomo

Metals and Alloys—supply most of the world's ceramic package substrates and enclosures. Popular alumina is a ceramic with a fairly low CTE of about 7 ppm/°C, high strength, and relatively simple processing characteristics. Aluminum nitride is another highly suitable ceramic material noted for very high thermal conductivity (higher than many metals) and it is used for package platform. However, there are few, if any MEMS applications that seem to require this level of thermal conductivity. Even the Texas Instruments DLP package that is exposed to intense light-source heating is made from alumina.

Metal as an enclosure material is not very common in the MEMS arena, but still may be useful for smaller, low-lead count chips, or very specialized chips, and complete *system-in-package* (SoP) concepts. Metal, when used for enclosures, is selected from low expansion and noncorroding alloys such as Kovar (Alloy 42). Kovar, originally developed by Westinghouse, is an alloy of iron, nickel, and cobalt (Fe-Ni-Co) that has a thermal expansion of 3.25 ppm/°C; about the same as glass. Therefore, it is often used where glass-to-metal or ceramic-to-metal seals are involved. This low expansion alloy has been widely used for making hermetic packages and since it seals to glass and ceramic they are now thermomechanically stressed. Other metal alloys include CuW (10/90), Silver (a Ni-Fe alloy), CuMo (15/85), and CuW (15/85) as they all have good thermal conductivity and relatively low CTE values. All of the above materials, in addition to Alloy-46, may be used for the sidewalls and lids. The most common plating is gold.

5.1.4 Organic plastics and their benefits

Organic polymers are long-chain molecules with repeating chemical structures that occur naturally, but now are mostly synthesized. The vast majority of polymers are organic, but a small percentage of inorganic polymers have been synthesized. The definition of "organic" once required that the material be derived from something that was alive or once living, but early incorrect assumptions made this view insufficient. Organic is now defined as molecules containing carbon atom(s) bonded to hydrogen; this helps to differentiate from obviously inorganic compounds like silicon carbide (SiC), an inorganic ceramic. Unfortunately, the widespread and casual use of the term organic in organic gardening and foods has added even more confusion. Our definition for organic polymers is: long-chain molecules containing carbon atoms within the structure, especially the backbone that may be joined to one another or chemically-bonded to other atoms, specifically nitrogen (N) and sulfur (S). The structure will have a repeating unit although this can be an oversimplification. Much of the body is made up of polymeric structures, and even DNA fits the polymer definition, signifying the extreme complexity that is possible for organic structures. Plastic is the generic name for useful synthetic or semisynthetic polymer materials that are designed to be molded into shapes, extruded

into films, spun into filament, or made into coatings, adhesives, and other practical articles, or materials.

The famous line from "The Graduate,"[2] ". . . Plastics, my boy, that's the future," is even truer today. Plastics are still the future and they will only get better as we finally make them into practical conductors and turn them into optical and electronic devices. They are incredibly versatile, much more than metals and ceramics. The complexity of nature is based on organic systems, not metallic or ceramic. Many nanostructures will become polymers as their length is extended; for example, *carbon nanotubes* (CNT) turned into ropes become polymers. Although electrically conductive polymers have been known for some time, they have not succeeded as metal replacements since properties are inadequate, processing is difficult, and stability has been poor. But nanotechnology offers real promise for nonmetallic conductors for ICs, *polychlorinated biphenyls* (PCBs), and packaging, perhaps in less than 10 years. The likely chemical structure for these conductors will probably be plastics. Plastics are arguably the most important material today, even though they were considered a commodity a few decades ago and the technology has seen its best days.

Materials have been so important to civilization that entire eras have been named after them—the Stone Age, Bronze Age, and so on. From a materials perspective, we are still in the Plastics Age and the day will come when we have plastic (organic) electronic devices in polymer enclosures on plastic circuits. Ironically, many who worked with polymers 20 or 30 years ago were told, and many believed, that the golden age of polymers had passed because all of the basic polymers had been invented. How wrong! Fundamentally new polymers continue to be invented, innovative processes are still being implemented, and imaginative new products come to the market every month. Much of emerging nanoelectronics is based on organic, polymerlike structures that may some day replace wires and silicon transistors. Although electronics has been considered the leading edge of technology, this field is far behind in the adoption of modern polymers, except for the housing, cases, and enclosures that hold the electronics products. There are thousands of plastics used in every industry making these materials the most widely used class of materials. They can literally be made into millions of blends and composites. More recently, organic polymers are being developed into electronic devices such as o*rganic light emitting diodes* (OLEDs). Perhaps such organic electronics will find usage in packaging technology.

Plastics can be grouped into just two broad categories—*thermosets* and *thermoplastics*. Thermoset plastics, like epoxies, are produced when monomers react to form long chains that are interlinked (cross-linked) to create megamolecules. Epoxies were the first broadly successful organic packaging materials and continue as the most widely used materials today. They are also used to make organic circuit laminates, like FR4 and BT. Since epoxies are thermosets, they are set by polymerization when

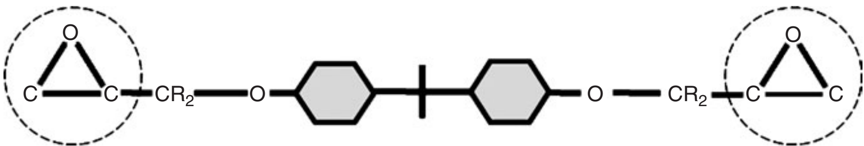


Figure 5.1 Epoxy structures.

heated to about 150°C or higher (ambient cure is also possible). A typical molding epoxy molding compound is made up of stoichiometric (reactively matched and balanced) amounts of epoxy resins and reactive hardeners, such as anhydrides.

The epoxy group has a strained ring consisting of an oxygen atom connected to two carbon atoms, which, in turn are connected to one another. This three-member ring strains the bond angle that would be *neutral*, or unstrained, if the ring were made up of a total of four or more atoms. Figure 5.1 shows epoxy structures. The strained-ring state makes the epoxy group very reactive, since energy is released when the ring opens up as the oxygen-carbon bond breaks. Hardeners or coreactants help in opening up the epoxy rings, so that the two resulting free bonds can react with specific chemical groups and bonds in the hardener and other epoxy rings. The result is complex polymerization that ultimately produces the megamolecules that we know as hardened epoxy. But the reaction rate can be slow without assistance from an accelerator, which can boost the rate by orders of magnitude and also lower the curing or polymerization temperature. An accelerator is like a catalyst, but it is consumed in the reaction to become a part of the molecular structure. A catalyst does not typically react and can often be used indefinitely. Figure 5.2 shows the

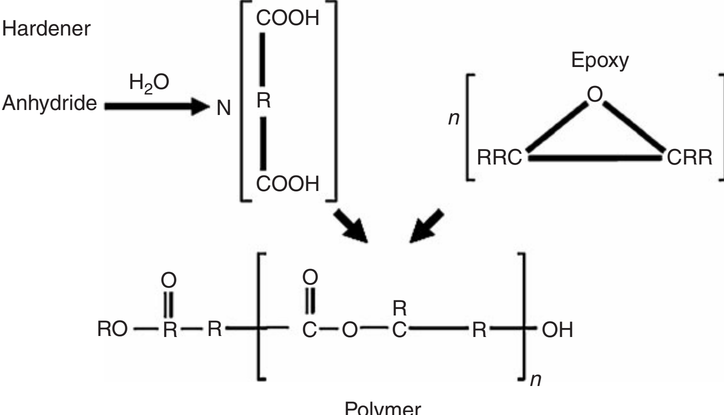


Figure 5.2 Epoxy reactions.

reactions. The properties of the resin mix will therefore depend on the epoxy resins (severally are common), the hardeners (more commonly one), and the accelerator. But the filler, which may be as high as 75 to 80 percent by weight, has a dramatic influence on properties. The main reason for adding filler—usually a minerallike silica—is to reduce the CTE of the epoxy from its high value of about 75 to 85 ppm/^{o}C to something much lower that will not cause excessive thermomechanical stress.

The other major polymer class is thermoplastics polymers which can be melted by heating since there are no confining cross-links. The key distinction between thermosets and thermoplastics is the cross-link. A cured epoxy part is more or less one giant molecule that can not melt. It was the nonmelting characteristic that made it a good choice for packages and circuit boards that needed to withstand the high temperatures of soldering. Early thermoplastics would soften and deform at below-solder temperatures, and they were not in contention. But that is no problem for today's materials which can have softening points of well over 300°C. Thermoplastics also have long chains, but they are independent (not cross-linked) so that thermal energy will cause a transition from solid to liquid state, while cooling returns the material to the original solid with virtually no property changes. Thermoplastics can therefore be reshaped because of this reversible phase change, and this is the basis for injection molding and other thermoforming processes. Plastic thermoforming is a very large worldwide industry that is highly diversified. Today's thermoplastics are superior to EMCs in critical categories, can take the abuse of lead-free soldering, have an order of magnitude better moisture resistance, can be rapidly shaped into precise 3D structures, and many can pass flammability standards without the addition of halogens, phosphorus, nitrogen compounds, or hydrates.

5.1.5 Epoxy limitations

Many now believe that thermoset polymers which are economically viable, especially epoxies, have reached a final "plateau" and will increasingly fall short as packaging requirements increase. Relatively high moisture absorption is an increasing concern and so is the need to add flame retardants. But epoxies are still the dominant polymer for electronics, where they are used in plastic packages, encapsulants, underfills, and circuit boards. While epoxies are notable for their balance of properties, they do not really excel in any particular area. In fact, without a significant level of fillers and modifiers, epoxies are not very useful in electronics. Substantial amounts of organic bromine compounds must also be added for epoxy to pass flammability standards. Encapsulants and underfills typically contain more filler than epoxy resin, in order to tame the high *coefficient of thermal expansion* (CTE)

that ranges from around 80 to 90 ppm/°C. And when it comes to water absorption, epoxy resin is a "sponge" compared to many other commercial polymers. Epoxy-based circuit board laminates require a substantial level of glass reinforcement to control their dimensional instability, as well as the bromine for flame retardancy.

Finally, the thermoset materials class cannot be recycled and reused like thermoplastics, which are typically reground and reused. The time will certainly come when the dubious strategy of selecting materials suitable for "burial and burning" is unacceptable. Then epoxies will be even more problematic since there does not appear to be a practical technology for reclamation. Thermoplastics, on the other hand, can be separated from inorganic materials and metals by methods that have been used for decades. Most communities recycle plastics. The day will certainly arrive, sooner than we foresee, when electronics is recycled and materials are reclaimed. Thermoplastic electronics will enable the outdated products to be turned in and replaced by the latest innovations with no waste. The use of thermoplastics includes the PCB and packages, not just the housing and will enable recycling and reuse as the correct environmental solution to waste control and resource management.

5.1.6 Metals versus ceramics versus plastics

Metals, as stated earlier, are not top contenders for MEMS packaging materials because of the necessary insulating of the electrical interconnects to allow them to pass through the electrically conductive enclosure. The MEMS materials selection therefore comes down to a choice between inorganic ceramics and organic plastics. We can choose alumina as the standard ceramic packaging material, but will have a more complex situation for polymers. We can assume that epoxy will continue to be the major thermoset plastic since that has been the case for over 50 years, and there are no thermosets on the horizon that could easily "dethrone" epoxies. Bromine will ultimately be removed for regulatory reasons, but properties will be much the same as they are now. However, epoxies, their well-established processes, and the infrastructure equipment are best suited for noncavity, overmolded packaging. Thermosets may turn out to be the best economical choice for capped MEMS devices that tolerate overmolding, but will not be the best option for cavity-style enclosures. Since many MEMS devices require a free space cavity package, thermoplastic may still be the right choice for nonhermetic and near-hermetic applications since they are readily formed into cavity packages.

First, we need to list candidate thermoplastic materials that can meet the basic packaging requirements. The first criterion must be thermal stability at the highest temperature that the package will experience during

first- and second-level assembly, or in actual use. The most thermally-abusive process that the package will encounter is soldering, and that process has become even more abusive since the lead-free initiative. The package material must withstand the maximum solder reflow over profile temperature. We need to use the values for lead-free solders since they are higher than the traditional tin-lead solders which will soon be obsolete. The upper limit for lead-free solders can range from 240 to 260°C when all things are considered. Table 5.2 shows the top candidates for packaging. Most people who work with thermoplastic packaging choose the *liquid crystal polymer* (LCP) class, so-named because the polymer chains orient into orderly crystalline structures even in the liquid state. These C-H-O based molecules are superb environmental materials that pass the V-O flammability rating without additives because of their compact molecular alignment. The efficient molecular packing also results in a high melting point and moderately good barrier properties. LCPs have been used for over a decade to make precision, moisture-resistant, dimensionally stable parts, such as optical connectors, so there is a wealth of practical knowledge available.

Commercial LCPs, with an order of magnitude and better gas barrier performance than epoxies, act more like glass when it comes to moisture. The challenge is to determine where and how to use such materials in packaging. But we appear to be at the right moment in terms of time and technology to adopt thermoplastics for packaging and circuitry. Thermoplastics have been considered for electronic packaging before, but for postmolded applications where the devices were subjected to direct contact with very hot molten resin, it is not an ideal process. Only a small number of devices were successfully molded with thermoplastics, mostly discrete types like transistors. Thermoplastics are just not a good material class for overmolding since they must be raised to their softening or melting point, which will be within 300 to 400°C range. Since thermoplastics can be melted repeatedly, candidates for packaging must melt above the solder assembly temperature. Thermosets, like epoxies, are much better suited for postpackage overmolding since these materials will initially melt (unpolymerized) at a lower temperature that can be

TABLE 5.2 High-Temperature Thermoplastics

Plastic	Water abs.%	MP	UL9 4	CTE @ 30% glass filler
LCP	0.02–0.10	280–352°C	V-0	0–12 ppm
PEEK	0.15	340°C	V-0	16 ppm
PPA	0.15–0.29	310–320°C	H-B V-0	22–40 ppm
PPS	0.01–0.04	280°C	V-0	19–27 ppm

LCP = Liquid Crystal Polymer; PEEK = Polyetheretherketone; PPA = Polyphthalamide; PPS = Polyphenylene Sulfide.

engineered; and that is the melting point of prepolymers before they are converted to polymers. Thus, the devices are only subjected to modest temperatures and pressure during thermoset overmolding. After polymerization, the thermoset will not melt and the resulting package can be soldered. But the situation is completely changed for premolded packaging where processing temperatures are inconsequential.

Thermoplastic resins are reasonably priced and widely available. Table 5.2 compares some of the best thermoplastics from the view of a packaging material. The infrastructure is also in place and there are many more injection molding machines than transfer molding presses. Although the packaging industry has mostly disregarded "thermoplastics thinking" for packaging, the MEMS' general requirement for cavity packages could become the entry point. Injection molding, as described in Chap. 4, is ideal for making cavities with precision features, and this is done everyday for billions of plastic parts, so why not for packaging? Now, back to the plastic materials selection.

LCP has recently entered the PCB product area as a high-performance flexible circuitry base. Tables 5.3 and 5.4 show some of the LCP properties of flex materials. The electrical and chemical values are relevant to packaging and are seen to be excellent. The low moisture absorption is valuable for stable high-frequency circuitry and provides a double payoff for packaging. Low moisture absorption for the enclosure improves both package reliability and electrical transmission performance where conductors and pass-through interconnects are in contact with the plastic.

While thermoplastics are the easiest dielectric materials to shape into cavity packages, their barrier properties, while good, are not as impressive as ceramics, which are fully hermetic under the MIL STD 883 criterion. The maximum thermal endurance of the best engineering plastics is not as high as ceramics, but since many plastics can survive repeated

TABLE 5.3 LCP Flex Laminate Properties

Property	PI 1	PI 2	LCP	Test
Tensile strength (kpsi)	50	42	15	D882, 64T
Elongation %	60	40	15	D882, 64T
Young's modulus (kpsi)	800	825	700	D882, 64T
Tear strength (g)	26.2	17.5	15.4	D1922-00A
Heat shrinkage % at 200°C	0.08	0.04	0.04	D2732
CTE (ppm/°C)	13	14	18	D696, 44
Moisture absorption %	2.4	2.0	0.1	D570, 63
CHE (ppm/%RH)	9	8	2	D570
Moisture trans. rate (g/cm^2/day)	4.2	3.8	0.4	F1249
Dielectric constant	3.3	3.1	3.0	D150
Dissipation factor	0.005	0.005	0.003	D149

Tested on 2 mil commercial film–data from 3M Co. (typical)

TABLE 5.4 LCP Flex Laminate Properties–2

Material properties	Value
Dielectric constant D_k	3.0
Dissipation factor	0.003
Water absorption	0.1%
Transition temperature	335°C
Solder heat resistance	280°C
Warpage at 200°C	1%
Coeff. thermal expansion (CTE) (ppm/°C)	16
Coeff. hygroscopic expansion (ppm/%)	2
Accuracy of thickness (%)	5%
Peel strength for copper foil (kgf/cm)	0.8
Chemical resistance	Excellent

BIAC LCP (Gore)

exposure to lead-free soldering conditions, this is not an issue except in a few extreme cases. Perhaps the Texas Instruments MOEMS DLP unit which gets exposed to significant heat from a high intensity light source is not a good candidate from the heat-load perspective, but this is an unusual application; and there are other requirements that are better met by ceramics. The materials choice for MEMS then comes down to selecting either a more expensive hermetic ceramic system or a lower-cost near-hermetic thermoplastic. The cost differential for high volume ceramic and thermoplastic packages suitable for a MEMS inertial device is estimated to be about 1:5; for example, the cost of materials and labor is 5× higher for a ceramic package. We need to keep in mind that the added cost for the ceramic package is not directly related to material cost differences; it is mostly about process cost.

At this stage of materials development, ceramic materials and metals are warranted and are the only options when full hermeticity is an established requirement. *Established requirement* means that it is determined by testing and not on a hypothetical basis that can be an excuse for risk aversion. While "always-do-it-that-way" strategies can appear prudent, they have been fatal to companies, and entire industries, who thought they could catch an innovative competitor if the idea turned out to be a good one. Plastics are clearly the optimum choice for "low cost–high volume" when it comes to high-precision complex structures that will be needed for advanced MEMS devices, especially any that handle materials.

5.2 Joining Materials

There are really only two basic methods of first-level assembly: *direct chip attach* (DCA), commonly called "flip chip," and wire bonding, since *tape automated bonding* (TAB) is a subset of wire bonding. Wire bonding has

continued to retain the title of being the most popular chip interconnection and this will continue into the foreseeable future. The most common joining material for wire bonding is thin, high-purity gold wire, although aluminum wire is used in limited applications and copper continues to gain a foothold. Since gold wire is the "gold standard" for wire bonding, the majority of electronic chips, and most MEMS devices, there are no materials selection issues here. But DCA is a totally different and still-evolving situation. There are probably even more joining materials than needed. The list includes solder bumps with various alloys; solder pastes applied to substrate; infusible bumps with solder caps; vacuum-deposited metals; directly formed metallurgical joints; pressure connections; isotropic conductive adhesive pastes; and anisotropic conductive films. Solders, whether applied to the substrate, or as part of the chip bump metallurgy, are mostly lead-free alloys similar to those now moving into assembly.

DCA can offer several advantages for MEMS including the formation of a protective, free-space region between the chip and substrate. The standoff or chip gap is defined by the bump height after assembly and any bump collapse that may result. A solder bump can collapse until the chip gap becomes zero if there is no restriction in the substrate bond area that can be moistened by the molten solder. The original C4 (actually C^4) is the acronym for *controlled collapse chip connection* that utilized pad area limitation for control. However, a more definitive approach for MEMS may be to fabricate nonfusible bumps as the guaranteed standoff, and add joining material that can collapse to form the bond without reducing the gap. Nickel bumps with solder caps could be used, or gold bumps with conductive adhesives, especially if low temperature assembly is required. Lead-free bumps and solder pastes are now available and should be the only materials under consideration.

5.3 Assembly Issues and Material Solutions

5.3.1 Protection during singulation

Once MEMS chips have gone through the final release step, they are vulnerable to mechanical damage and can be very sensitive to contamination. Contamination can be fatal where such tiny moving parts are involved. See Fig. 5.3 for an idea of how a small particle can immobilize a micromechanical device like the Texas Instruments micromirror chip. The DLP has 1.3 million mirrors that are 16 μm × 16 μm, and every one must remain operable. Assuming that the particle can lodge against any of the four edges, means that there are over five million locations that are in jeopardy. During operation, the 1 μm spacing momentarily drops to 0.2 μm. The active side of the wafer must therefore be protected during singulation, which usually involves sawing with a diamond blade. Even relatively clean laser singulation methods, and snap-to-singulate methods require

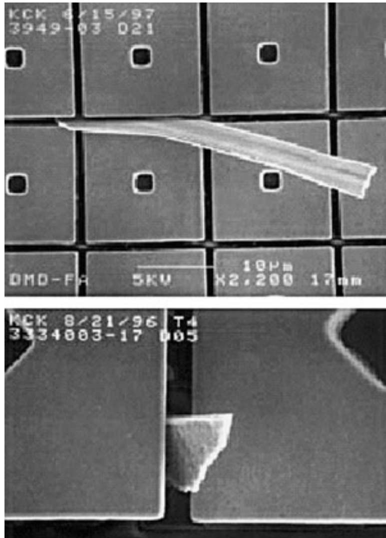


Figure 5.3 Texas Instruments DLP with contamination.

wafer face protection. One exception is capped MEMS, but this process is presently restricted to inertial sensors that do not require any inputs beyond electrical.

Plastic adhesive films have been used to protect the active face of the wafer, including double-side types that allow two wafers to be mated face to face. Other strategies have relied on thin plastic films that can be prepunched to form relief holes, so that no material contacts the MEMS' moving parts that could be damaged or contaminated by adhesive. UV release tapes can be valuable. Coating is also being used that can be photodefined. The materials, whether free-standing films or liquid coatings, are mostly modifications of the standard products used for electronic wafers. Many dicing films for MEMS use special polymer adhesives, especially UV curing and/or debonding, and some are removable with alcohol. MEMS dicing and protective tapes are usually clean and do not tend to leave any residue on the wafer or devices.

5.3.2 Die attach adhesives

Die attach adhesives must accommodate two special requirements of MEMS—low stress and low contamination. While conventional modified epoxy adhesives can be used, other polymers may offer advantages. Silicones can have very low modulus values, and products for MEMS have been introduced. Dow-Corning, of Midland, Mich., for example, offers two low-stress, photoimagable, silicon-based products—the WL-3000 and WL-5000 Series. Both product lines are low-modulus and low-cure-temperature

materials designed to produce highly reliable assembles. According to Dow-Corning, "They are also suitable for MEMS, biochips, and ICs that incorporate low-k dielectric layers." Many other materials suppliers have customized products for MEMS, having recognized this area as one of the growth markets. Film die attach products can also be considered and the methods were covered in Chap. 4, where process options were compared.

5.3.3 Lid seal materials

Hermetic sealing of metal lids to metal bodies requires a metallurgical joint. The materials used are generally solders or brazing alloys (essentially high-temperature solders). Welding, although requiring higher temperatures, can also be used where the joining material comes from one or both adherents. Lid solders include gold-tin (80Au/20Sn); tin-silver-copper (95.5Sn/3.8Ag/0.7Cu); and tin-gold (80Sn/20Au). Lids are available with plated sealing materials that can form eutectic alloys during the sealing process. A nickel barrier is first plated, followed by gold or gold-tin cladding. Ceramic lids can be sealed with solder if both surfaces are metallized, but "glass solders" are more economical. The glass bonding agents can be pastes or preforms. Low temperature glass seal materials include silver-glass compositions that can bond below 400°C.

Near-hermetic sealing typically utilizes polymer adhesives in the form of pastes for printing and needle dispensing, and film preforms that can be thermoplastics or B-staged thermosets. Thermoplastics should be high temperature polymers with good barrier properties like LCP. Glass lids can be sealed to metal, ceramic, or plastic enclosures with thermoset films or pastes, thermoplastic films (that can be formed in situ from pastes), or UV-curable adhesives. Thermoplastic can be melted and sealed with *infrared* (IR) or near-IR energy, especially from lasers, but they must absorb energy and convert it to heat. IR/NIR absorbers can be added. Colorless and colorant type dyes can be added and are available from GENTEX as clear-weld. However, a small amount of carbon black in the resin will suffice. See Chap. 4 to compare the lid sealing processes.

5.4 In-Package Additives

MEMS is the most unusual device that the packaging community has encountered yet. A few devices must have a vacuum even to function since inert gas molecules can alter the mechanical motion of functions involving high-speed oscillation. But this is not a new challenge, since many electronic and optoelectronic devices and systems have required a vacuum. Other MEMS and MOEMS devices require low humidity and low oxygen environments. Pure electronic systems and optoelectronic products, including

lasers and some of the new displays, like OLEDS, may also require very low H_2O and O_2 values. Still other MEMS devices could require higher levels of humidity for lubricity or for actual lubricants. There is a general need for antistiction liquids, solids, and vapors;—whatever works best for a given device and package. In addition, many advanced MEMS devices may need access to external materials or even to the atmosphere. When all is said and done, MEMS has the widest and most diversified requirements for in-package content.

5.4.1 Getters

Getters, as mentioned previously, are selective scavengers or attractors, designed to capture and remove undesirable substances from the inside of the package. They are essential to some packaging systems where contaminants and by-products are likely to—and would— "kill" the device. Getters were used in early vacuum tubes where reactive metals consumed oxygen before it could degrade hot filaments. Today, getters are used in *hirel* packages, including military and satellite communication modules. The same types of getters can be used for MEMS, but new products will probably be needed. Several agent-specific getters, as well as combinations, are already available. The list of getters includes several gases, liquids, and solids. Important gas getters include oxygen and hydrogen, both found inside of the hermetic package and known to be potentially harmful. The most important liquid or vapor getter targets water, and the class is generally referred to as moisture getters. Some of the moisture getters also trap ammonia, sulfur dioxide, and other harmful species that can be found in packages. Getters for solid micro or nanoparticles are general purpose and intended to capture small particles of any composition, including those generated by the device itself. While other getters can be designed, moisture and particle getters are the most important types for both high reliability electronics and MEMS. The Texas Instruments DLP package, for example, uses a combination of moisture and particle getters. Moisture and particle getters are especially important for MOEMS devices and can be combined into a single multipurpose material. Table 5.5 list common getters.

TABLE 5.5 Getters

Type of getter	Mechanism
Moisture	Desiccant
Oxygen	Active metal
Hydrogen	Palladium or palladium oxide
Particle	Tacky polymer
Organic vapors	Activated carbon

Traditional hermetic packages used in military, space, medical, and other applications often require high reliability and have an upper limit of 5000 ppm of water vapor content at the time of fabrication. Package leak rate is limited to 10^{-8} atm-cc/sec, to prevent entry of significant moisture during the device's expected lifetime. But it is difficult to manufacture a hermetic packaging for microelectronic devices with low water vapor content and to maintain it during its lifetime of many years. There are mechanisms for water vapor to enter the package interior that includes seal leakage, water generated during the sealing process, and moisture outgassing from adhesives, or even the package. The best long-term reliability assurance requires the use of getters.

Moisture getters contain potent desiccants dispersed within a permeable matrix that is typically a polymer. Desiccants can be common inorganic compounds that form hydrates by combining with one or more molecules of water. The chemical attraction for water molecules is the "pump" that dries out the package chamber. Zeolites and other mineral type compounds are used in many of the moisture getters. The solid desiccant is finely dispersed and suspended within a plastic film that can be attached to the inside of the package. While film is more common, getters can also be supplied as solvent-borne pastes, which can be dispensed into the package or onto the lid, followed by thermal hardening. Getters may require activation by heating since the desiccant can pick up moisture during storage and application. Heat activation before sealing the package can be used to dehydrate the compound back to a full-capacity dry state. Also note that some ceramic packages can absorb water, so that the package is, effectively, the getter.

While moisture is generally bad for any electronic device, it can be especially troublesome for all MEMS products. Moisture will induce a surface contact phenomenon known as *stiction*. Stiction is a high intersurface attraction between two parts making contact that causes them to stick together, often permanently. A very high force is required to move things apart or start components moving. It can require a very high initial force to start a mechanism moving if stiction can not be overcome, and it will mean the need for excessively large motors. Even tiny mechanical stops for mirrors are subject to stiction. Stiction occurs in the macroworld but goes unnoticed because the forces are small. However, extremely low mass and relatively high surface area of MEMS devices makes it a major problem in the nanoworld.

But what does this have to do with moisture? Water molecules on a surface can act like a "glue" to greatly increase stiction. And once stuck, a mirror may remain "dead." Relative humidity values of 20 percent or less are said to reduce stiction.[5] Also, H_2O is generally bad for optics since it can fog lenses, corrode mirrors, and condense on windows.

A commercial moisture getter, like STAYDRY SD1000, from Cookson Semiconductor Packaging Materials (CSPM), is designed for applications

up to 400°C. These products ingest water vapor and other corrosive gases such as ammonia, sulfur dioxide, and hydrogen sulfide. When fully cured, the moisture absorbing capacity is more than 300,000 ppm/in^2/mil of coating in a 1" × 1" package of 1.5 cm^3 free internal volume at 150°C. The capacity increases by five times at room temperature.

Particle getters are usually designed as a multiple function system. A common multiple getter, like STAYDRY GA2000-2 (CSPM), is a two-part dual function system that becomes very tacky when cured. It functions both as a particle and moisture getter, and has been used for applications requiring p*article impact noise detection* (PIND) testing and increased operating life in hostile environments. Such getters meet or exceed the limits as stipulated in MIL-STD-883, Method 5011.3. Many particle getters can also be printed on lids or needle dispensed. Particle getters appear to be valuable for mirror arrays and other movable MEMS devices. Combination moisture-particle getters are now being used for MOEMS. The Texas Instruments DLP package uses solid strip moisture getters based on zeolites.

5.4.2 Humidity control agents

Studies by Sandia National Laboratories have shown that very dry packages increase wear on MEMS elements that make mechanical contact. Water vapor apparently acts as a lubricant by adsorbing onto silicon surfaces that will normally have an oxide layer that is hydrophilic. Higher moisture levels may therefore be beneficial to classes of MEMS devices that have bearings and other motion contact constructions. At the same time, high relative humidity can degrade metals and metallic interconnects. A nominal rh value of about 40 percent has been suggested. See Fig. 5.4., Moisture versus wear. Assuming that a ~0 percent rh value is optimum for some devices, the question is how to achieve this low value and maintain it, since materials can both consume and release moisture. Moisture getters all tend to remove moisture to achieve a low value by chemical reaction or strong adsorption, so they do not appear to be an option.

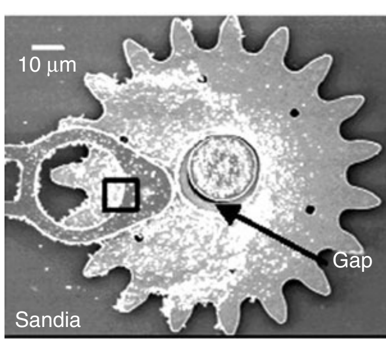


Figure 5.4 Moisture versus wear from Sandia.

Many chemical compounds, especially hydrates, form equilibrium with water vapor and can thus maintain a specific relative humidity. You may recall seeing constant humidity desiccators in laboratories made up with a specific hydrated compound. It may be possible to make getterlike systems using such hydrates' help in a permeable vehicle, including plastic.

5.4.3 Antistiction agents

One attractive approach to tackle the stiction problem is to provide low-energy surface coating in the form of an organic passivation layer on the inorganic surface. Texas Instruments uses a fluorinated fatty acid *self-assembled monolayer* (SAM) on the aluminum oxide surface in their *digital micromirror* device (DMD),[3] while Analog Devices, Inc. (ADI) has used a liquid silicone fluid that was vaporized by heating.[4] However, ADI now coats the surfaces of their inertia sensors using thermal evaporation of silicone polymeric materials at the packaging stage after the device is completely released. Low energy coatings can not only eliminate or reduce capillary forces and direct chemical bonding, but also reduce electrostatic forces if the thin organic layer is directly applied to the semiconductor substrate without the intervening oxide layer.[5,6]

Another much-advocated approach is the formation of siloxane SAMs on the oxide terminated surface; and this appears to be the mechanism that operates in some of the ADI disclosures. Universities have explored antistiction coatings in MEMS products to develop improved materials and chemical processes. The goals are to define chemistry that is simple and reproducible; coatings that are monolayer and covalently bonded to the substrate; coating processes that are compatible with dry or aqueous etching processes; and resulting monolayers that are chemically and mechanically stable under processing and operating conditions.

Jun and Zhu[7] have proposed a coating process using surfactant. One end of the group is selected to provide low surface energy, such as a highly fluorinated group, while the X group is chosen to selectively react with the solid surface of interest for covalent linkage. This is the common principle used for surfactants and substantive surface modifiers like 3M's Scotchgard and other stain and water repellants. Figure 5.5 shows the principle that has been used for decades to modify all types of surfaces, including silica and metals.[8]

Kim describes newer chemistry for a new surface modifier, dialkyldichloromethylsilane, $(CH_3)_2SiCl_2$, for stiction-free silicon surfaces. Trialkylmonochloride $(CH_3)_3SiCl$ is also said to work well. The material rapidly deposits on the chemically oxidized silicon surface at room temperature and successfully prevents stiction for long cantilevers (3 mm) during use, as well as during the release step. The modified surfaces are said to exhibit high hydrophobicity, long-term stability, and thermal stability. Advantages are: ease in handling and storage of the

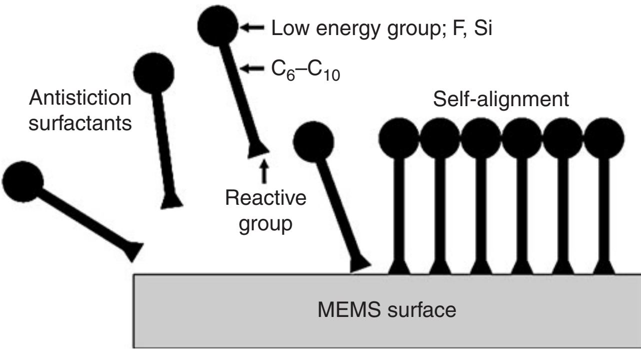


Figure 5.5 Surfactant monolayer formation.

solution, low temperature dependence, and low cost. In addition to the new modifier molecule, the simplified process of direct release right after washing the modified surface with isooctane was proposed to cut the processing time.[9] Many papers describe somewhat similar treatments with alkylchlorosilanes with similar results. However, Ashurst reports work with alkenes (C=C–) that can bond directly to silicon, without first oxidizing, as is required with chlorosilanes.[10]

Parylenes should also be considered as thin solid plastic coatings for antistiction, and the application process has been described in Chap. 4. The CVD coating process will produce more than the monolayer that the chemical treatments generally create. This may interfere with some mechanical operations, but the added thickness could be useful for antiwear; thickness can be as low as 100 A. The most suitable parylene is one that is fluorinated, since substitution of fluorine for hydrocarbon groups and even chloro (Cl) groups will give the lowest surface energy and usually the highest thermal stability. The only fluorinated parylene that appears to be commercially available is Nova HT, which was originally introduced as Parylene VIP AF-4 by Specialty Coating Systems (Cookson Electronics). Since the material was originally developed as an interlayer dielectric, very high-speed, fine-pitch IC, it should be compatible with MEMS wafers and devices. Figure 5.6 shows how the parylene polymer is formed from the dimmer in a vacuum pyrolysis chamber while Fig. 5.7 shows the structure for Nova HT that is optically clear and could be suitable for MOEMS special light controllers. Parylene has been used as a MEMS fabrication material[11] which suggests its potential value as a MEMS-compatible coating.

5.4.4 Lubricants/antiwear agents

Several researchers have proposed adding volatile lubricants to MEMS packages to reduce friction and wear. Many, if not all, of the antistiction agents may have lubricity properties, however. Water also appears to act

Dimer Monomer Polymer

Vaporize 100–150°C 1.0 torr

Pyrolyze 650–750°C 0.5 torr

Deposit 20–40°C 0.1 torr

DPX PX PPX

Figure 5.6 Parylene formation.

as a lubricant, based on the Sandia findings that suggest that a monolayer of water or perhaps more, attach to the silicon or silicon oxide surfaces of parts in contact. This layer apparently isolates the parts from contact and allows them to move on the water film. But there are many reasons to reduce or even exclude water from a MEMS package, and even more reasons to keep relative humidity low in MOEMS systems. The small size of MEMS parts means that they exert so little force that conventional lubricants do not work. Oil molecules are too large and viscous and would tend to restrict motion. The current trend is to use solid lubricants, especially self-assembling monolayers or fluorocarbon compounds. But these thin coatings are also subject to wear and are not self-healing or replenishing.

Dr. Sundararajan did extensive work for his Ph.D.[12] thesis on the problem of MEMS friction and lubrication. He carried out research using *atomic force microscopy* (AFM)-based experimental techniques measuring friction on polysilicon micromotors. He developed techniques to measure

$(CF_2$ — $CF_2)_n$

Figure 5.7 Parylene Nova HT structure.

static frictional forces in the devices and generate a coefficient of static friction. The unlubricated motor was the baseline. A molecularly thin bonded layer of *perfluoropolyether* (PFPE) lubricant, available as Z-DOL (Monti Edison), reduced the static friction substantially and also made the contact interfaces insensitive to the environment. However, excess liquid lubricant increased friction up to three times higher than unlubricated parts, although the liquid layer was very thin. He concluded that solidlike hydrophobic lubricants appear to be ideal for lubrication of MEMS. We might also suspect that low surface energy of the lubricant is important since fluorinated compounds have very low values. Once again, Nova HT fluorinated parylene, described earlier, may be suitable as an antiwear coating.

5.5 Conclusions

The package design and materials are always important, but when it comes to hermetic performance, the enclosure composition is paramount. Metal and ceramic enclosures provide assured hermeticity but at a substantially higher cost than plastics. Plastics achieve most of their cost savings by enabling very efficient processes, like transfer molding and injection molding. Thermoplastic materials provide the lowest-cost cavity packages, are environmentally benign, and can be recycled, but do not provide full hermeticity as defined by MIL STD 883. Ceramic materials are the best candidate when hermeticity is absolutely required. Thermoset transfer molding is only practical for capped MEMS since it removed the requirement for free space. Injection-molded thermoplastic materials are the optimum choice for cavity packages when absolute hermeticity is not required.

In-package additives are an important material class for MEMS since the package's internal environment can be critical. Getters may be useful, and even critical for MOEMS devices that are sensitive to moisture, and disabled by tiny particles of contamination. Antistiction additives and coatings are useful for most MEMS devices and essential for some. Lubricants may also be necessary when mechanical elements make contact. “Dry” lubricants are highly preferred, and liquids may not even be viable. Low surface energy hydrophobic monolayers may reduce stiction, friction, and wear.

References

1. Gilleo, K., *Handbook of Polymer Thick Film*, Kluwer Academic Publishers, Norwell, Mass.,1995.
2. “The Graduate,” movie directed by Mike Nichols, screenplay by Calder Willingham, starring Anne Bancroft, Dustin Hoffman; produced by Embassy Pictures Corp. and Lawrence Turmin Inc., 1967.

3. Hornbeck, L. J., U.S. Patent 5602671, 1997.
4. Martin, J. R., and Y. Zhao, U.S. Patent 694740, 1997.
5. de Boer, M. P., and T. M. Mayer, *MRS Bulletin*, Vol. 26, pp. 302–304, 2001.
6. Maboudian, R., *Surf. Sci. Rep.*, Vol. 30, pp. 207–269, 1998.
7. Jun, Y. S., X. Y., Zhu, *Adh. Sci. Technol.*, (special MEMS issue, 2003), in press.
8. Gilleo, K., E. Tajkoski, "Sulfur subst. bis(polyfluro-dicarboxy acid) surfactants, water-repellants," U.S. Patent 3,828,098, 1974.
9. Kim, B., et al., "A New Organic Modifier for Anti-Stiction," *Journal of Micromechanical Systems*, Vol. 10, No. 1, pp. 33–40, March 2001.
10. Ashurst, W. R., et al., "Alkene Based Monolayer Films as Anti-Stiction Coatings for Polysilicon MEMS," *Proceedings of Solid-State Sensor and Actuator Workshop*, Hilton Head 2000, Hilton Head Island, SC, pp. 320–323, 2000.
11. Meng, E., and Y. C. Tai, "A Parylene MEMS Flow Sensing Array," *Technical Digest, The 12th International Conference on Solid-State Sensors, Actuators and Microsystems* (Transducers '03), Boston, pp. 686–689, 2003.
12. Sundararajan, S., "Micro/Nanoscale Tribology and Mechanics of Components and Coatings for MEMS," Ph.D. Thesis, Ohio State University, 2001.

Chapter

6

From MEMS and MOEMS to Nanotechnology

Nanotechnology is a field that has not been clearly defined, and there may not be a single definition that, when taken alone, has enough significance. It may be easier to define what nanotechnology is *not*, rather than what it is. A working definition will be tackled in the next section, but for now, let us use an *exclusion filter* to examine MEMS from a nano perspective. About the only thing presently agreed upon is that nanotech materials, structures, and devices do not extend beyond 100 nm or 0.1 μm maximum dimensions. However, a few have suggested that the nanotechnology working range be stretched all the way up to 500 nm; but that would only add more ambiguity and move nanostructure squarely into the microworld. Although MEMS is often mentioned, and even grouped with nanotechnology, we need to determine if there is a logical basis for inclusion today. We will find that MEMS devices are much too large to be moved from the microworld where they started.

We need to measure some typical MEMS feature sizes against the 0.1-μm limit—our qualification "nanostick." Most of the skillfully crafted MEMS silicon-mechanical machines and such from Sandia National Laboratories are gigantic when scrutinized under the tiny nanotech viewing glass. Gears can easily be 100 μm in diameter, making them 1000 times too big for the 100-nm (0.1-μm) ruler. Also keep in mind that the nominal size of a nano object is 50 nm or 0.05 μm, and that the smallest nanoparticle is 0.001 μm. Figure 6.1 shows a section of a MEMS gear with a 40-μm reference line. Figure 6.2, also from Sandia, shows a smaller 50-μm gear compared to a red blood cell and a pollen particle. Even when we measure the world's most sophisticated MEMS machine ever manufactured, the mechanical parts are much too big for nanoscale.

Copyright © 2005 by The McGraw-Hill Companies, Inc. Click here for terms of use.

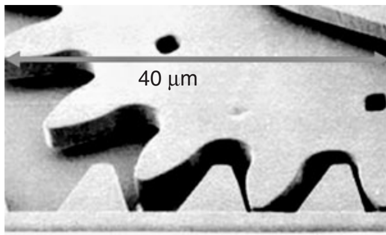


Figure 6.1 Sandia gear and 40-μm reference.

The Texas Instruments DLP MOEMS device contains 1,300,000 micromirrors that are 16 μm on each side. This 16,000-nm feature size is far over the limit and the DLP is clearly beyond the nanotechnology size range. There may not be any significant payoff in shrinking the chip, so the DLP could stay in this size range indefinitely.

Continued analysis will show that just about all MEMS and MOEMS devices have feature sizes that are easily excluded by the maximum 100-nm size limit and should not be classified as falling in the nanotechnology domain. But what happens if MEMS does get below the 100-nm scale? Some have suggested that shrinking MEMS magically produces nano-electromechanical systems (NEMS). While this may be accurate, does it really matter? Will the fabrication processes and functions be any different? Probably not, since today's most modern semiconductor fabs are building chips with nanoscale features and the same laws operate. Although continued shrinkage will cause quantum-effect problems, in a few more years when the size gets down below 10 nm, things really will get strange. Figure 6.3 shows a Texas Instruments micromirror with a 16-μm arrow across the width. A 100-nm line would appear as only a tiny speck, and we

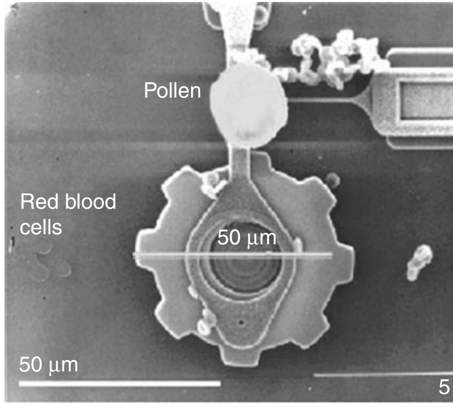


Figure 6.2 Sandia MEMS versus pollen versus blood cell.

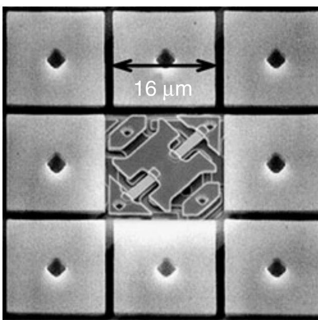


Figure 6.3 MOEMS micromirror size comparisons. (*Source: Texas Instruments.*)

would not even notice a 1-nm line. And finally, to get an overall size perspective, Fig. 6.4 compares the macro, micro, and nanoworlds to familiar objects. Nano is very, very small—the size of some atoms. And atoms are mostly empty space, as some may recall.

Microelectronics has quietly descended down below the 100-nm feature-size boundary and some of the commercial chips now have 90-nm features; soon we will move to the 65-nm mode. But the nanotechnology community is not likely to start referring to these small, but standard, products as nanotechnology. They are simply conventional solid state electronics fabricated at the nanometer scale—a monumental accomplishment nonetheless. The nanoelectronics terminology is being (hopefully) reserved for fundamentally

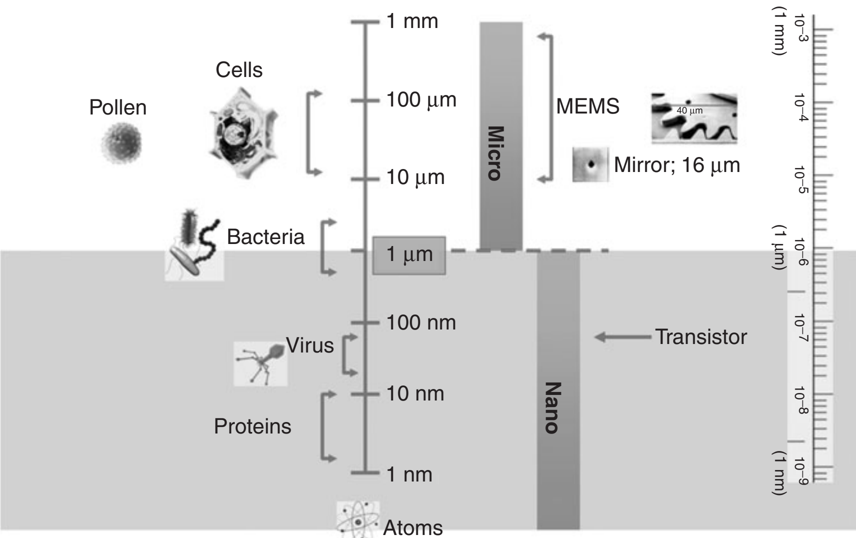


Figure 6.4 Scales in the different worlds.

new nanoscale devices, such as carbon-nanotube transistors. So why try to force-fit MEMS or even NEMS into the nanotechnology field? MEMS is presently a clearly defined and distinct technology that stands on its own. There are millions of MEMS products out in the field as a testimony to the success of micromechanical devices. This is not to suggest that nanotechnology will not eventually craft tiny electromechanical devices, but will use different materials and principles than those found in today's MEMS world. These will be true NEMS. Already, very basic nanomotors have been constructed in the laboratory and more will come. One has been made from a single strand of DNA by the University of Florida. The motor is so small that hundreds of thousands could fit on the head of a pin, curl up, and extend like an inchworm. Nanomechanical concepts will certainly tap into biology and utilize molecules, and also many other areas.

A better issue is to determine if we can use nanotechnology to enhance MEMS right now. We should consider processes, materials, and devices. Before looking down this path, let us try to get a better hold on what nanotechnology actually is.

6.1 Definitions Are Important

Nanotechnology has proven to be more difficult to define than to practice. Part of the problem may be the result of offering very large incentives for research programs. When nearly a billion dollars, in the United States, alone, is offered for research proposals, the scope of the endeavor and the definition of the technology can expand beyond original boundaries. Nanotechnology is not a single science but more of a tool set, techniques, and principles; a kind of template to overlay; that can be applied to all of the sciences and engineering disciplines. Specialists in every technical field view nanotechnology from their own perspective and emphasize what they know best in this age of specialization. Chemists realize that nanotech is all about chemistry—the assembly and manipulation of molecules. Physicists will recognize the quantum characteristic in nanotechnology and move to the quantum range of 1 to 10 nm, and this is already happening with quantum dots. (The wavelength of an electron is ~10 nm; the Heisenberg Uncertainty Principle requires that if two conductors are separated by 1 to 2 nm, there is an equal probability that the electron will be in either conductor percolation or leakage effects. Quantum effects begin to operate below 10 nm.)

Some mechanical specialists may be inclined to see nanotech as a scaled-down world where the nuts, bolts, and beams are molecules with specific shapes that can be manipulated and connected together to build tiny machines (bottom of strategy). They are all correct.

The chemical fraternity has some advantage however, since chemists have worked at the nanoscale and even the subnanoscale since the 1800s,

if not earlier. Chemistry is adept at making molecules big enough to fit the common one nm to 100 nm range, and it may seem like just more chemistry. The chemistry orientation is especially valid for carbon-based structures. "Bucky balls" or "fullerenes" (named after Buckminster Fuller) are three-dimensional (3D) carbon-based molecules that fit the nanotech definition and were synthesized using chemistry. And if these structures are too simple, chemical reactions can produce carbon nanotubes (CNTs) that have become the most fundamental building blocks of nanotechnology. CNTs to an organic chemist are nothing more than six carbon-benzene rings fused into a 3D structure that looks like a molecular roll of chicken wire. The ability of chemistry to synthesize molecules that are nanoscale, some that are smaller and others that are larger, blurs the distinction between "Nanotech 101" and advanced chemistry. This may have motivated some nonchemists to write nanotech definitions that exclude chemistry (along with biology) as too-haphazard a process.

While nanotechnology definitions still remain murky and too numerous; any that exclude mass chemical and bioreactions as too imprecise, random, and haphazard are exceedingly limiting and will be ignored anyways. The chemistry of nature, best exemplified by DNA reactions, displays remarkable precision (replication) as the equivalent of a million pages of code are faithfully copied by millions per second over and over again. Chemists, such as Professor Richard Smalley, use chemistry to make nanomaterials, like CNT. Smalley was awarded the Nobel Prize in chemistry for his work in the field of nanoscience (fullerenes). The American Chemical Society (ACS) routinely reports on nanotechnology, covering the topic at conferences and in journals. Apparently, chemists believe that they can be nanotechnologists without throwing away test tubes and reactors and replacing them with atomic tweezers. But, chemistry is just a part of nanotechnology and all the other disciplines are also participating. Biology, mechanics, physics, optics, and others can adopt, utilize, and contribute to nanotechnology. And if a microbe is eventually engineered to grow nanomaterials, the concept would certainly fit nanotechnology, but with a biological perspective.

Nonetheless, some continue to define nanotechology in a way that excludes mass reactions—and this is a mistake. Most of the practical nanotechnology is the product of mass chemical reactions, including the increasing number of commercial implementations. It is certainly acceptable to view nanotech as the assembly of molecular structure, one atom at a time using atomic manipulators, but this is only one aspect. This atom-at-a-time approach has become known as "bottom up" while the mass reaction approach is "top down." Semiconductors would fall into the top-down category since we start with a wafer made up of billions of atoms and modify it by adding some atoms and subtracting others. A bottom-up chip would be made by placing millions of atoms of silicon in just the right locations along with dopants and metal atoms.

The originator of the bottom-up strategy is K. Erik Drexler, who envisioned making small machines, atom-by-atom, until they reached an operational state in his "Engines of Creation."[1] To overcome the manufacturing overload of placing trillions of atoms in place, a nanorobot would be the first breakthrough target. Once the first robot was built, it would build robot number 2, who in turn builds number 3, and the rest gets quite easy. Many scientists attacked the proposal as completely impractical and offered scientific calculations; but many others have affection for the bottom-up definition that has already been demonstrated on a very small scale. IBM, for example, wrote "IBM" on inert gas atoms using their atom force manipulator; it took all day, however. The expected "bottom-up versus top-down" battles ensued, including the classic, Smalley (Nobel Prize-winning chemist) versus K. Erik Drexler (self-taught technologist) dialogues. The battle of big words about small things was fought in print and probably did not settle much. The chemists, including the author, sided with Dr. Smalley and the other camp backed their visionary leader. And some seek to simplify things by referring to the bottom-up approach as *Drexlerian nanotechnology*.

Still the questions remain, "What is nanotechnology?" and "Is it bottom up, top down, or both?" Should we employ mass processes or should it really be only one atom at a time? The U.S. government, aware of all the confusion, has enlisted help from the National Institute of Standards and Technology (NIST) to more clearly define nanotechnology. Today, there are still widely differing and often contradictory definitions. The Internet lists almost 200,000 hits for "definition: nanotechnology" and there is still no consensus. Drexler and the Foresight Institute that he founded, defines it as "technology based on the manipulation of individual atoms and molecules to build structures to complex, atomic specifications." But what does *manipulation* mean? It is not listed in the Foresight glossary. A mechanical engineer may manipulate an atom with an atomic force device while a chemist may use catalysts, temperature, and pressure to assemble atoms into molecules. Chemists see themselves as molecular manipulators.

The National Science Foundation (NSF) weighs in with its web-listed definition, "Research and technology development at the atomic, molecular or macromolecular levels, in the length scale of approximately 1 to 100-nm range, to provide a fundamental understanding of phenomena and materials at the nanoscale and to create and use structures, devices, and systems that have novel properties and functions because of their small and/or intermediate size. The novel and differentiating properties and functions are developed at a critical length scale of matter typically under 100 nm. Nanotechnology research and development includes manipulation under control of the nanoscale structures and their integration into larger material components, systems, and architectures. Within these larger scale assemblies, the control and construction of their structures and

components remains at the nanometer scale. In some particular cases, the critical length scale for novel properties and phenomena may be under 1 nm (e.g., manipulation of atoms at ~0.1 nm) or be larger than 100 nm (e.g., nanoparticle reinforced polymers have the unique feature at ~200 to 300 nm as a function of the local bridges or bonds between the nanoparticles and the polymer)."

NASA delivers a much shorter but very useful definition; "nanotechnology is the creation of functional materials, devices, and systems through control of matter on the nanometer length scale (1 to 100 nm), and exploitation of novel phenomena and properties (physical, chemical, biological, mechanical, electrical . . .) at that length scale." This definition sets the size limits, lays down basic principles, and allows for both top-down and bottom-up processes. This is the definition that will be used in this chapter.

6.2 Combining Nano and MEMS

Earlier, a comparison between MEMS and MOEMS feature sizes indicated that these devices do not fall within any of the nanotechnology definitions, although all the three terms are often grouped together, especially by the media. A nearly invisible carbon nanotube and a silicon accelerometer have very little in common. But is it still possible to use nanotechnology to enhance MEMS or vice versa? It should be possible to use nanopowders and other materials in MEMS devices. Since many nanomaterials have unusual optical properties, it should be possible to use them in MOEMS devices. MEMS pumps, values, and material transporters may be able to handle nanopowders. And there is no doubt that nanotechnology can be used for MEMS packaging since it has already been applied to electronic packaging materials.

6.2.1 Nanomaterials added to MEMS and MOEMS devices

One of the very few genuine examples of combining MEMS with nanotechnology is the IBM MEMS DNA detector that uses nanoparticles as attractors on thin and movable silicon beams. This hybrid DNA system was announced by IBM researchers at the company's Zurich research center in 2001, in tandem with the University of Basil which assisted the former. This MEMS device is actually powered by external agents, but still falls within a MEMS definition since mechanical motion creates electrical signals just the way it does in MEMS inertial sensors. Tiny coated cantilevers are selectively deflected by DNA fragments and the stress of curvature is reflected in a change in electrical signal output. The array of cantilevers is made selectively attractive by treating it with specific strands of DNA. Different fragments made up of DNA complementary

strands bind naturally to specific cantilevers when a sample is introduced. The chemical bonding process creates stress that deflects the cantilever. This effect has been applied to detecting damaged DNA sequences, since a single base mismatch will cause a different stress—indicating the presence of a damaged fragment. The device is shown in Fig. 6.5.

6.2.2 MEMS to handle nanomaterials

Fluidic MEMS devices that deal with nanoparticles should be feasible, but there is not much work reported here. A search for "MEMS + nanotech," while generating over 100,000 hits, shows that the linking is a literal one and not a technology convergence.

6.2.3 Nanocomponents for MEMS

Nanodevices can be of value to MEMS devices. One area that seems to fit is nanofilters made from CNTs and other very thin and very long structures such as nanofibers. Researchers have built high-density filters from CNTs and other high aspect ratio materials that look like nonwoven materials, but on a much smaller scale. These parts should be useful to do basic filtering, but also in separating larger molecules. Red blood cells, for example, can be excluded by a nanofilter to allow serum to enter a MEMS analyzer or some similar device. Figure 6.6 shows a CNT type filter compared to a red blood cell. This is just one mechanical separation example that could become a solution for some of the MEMS "restricted access" problems.

Nanostructured surfaces can be used as electrical probes, especially for biological measurements. Bio-MEMS will be able to apply these types of nanostructured probe surfaces in the future. Work at NASA-Ames has led to the development of *chemical vapor deposition* (CVD) nanofibers. The resulting *multiwall nanofibers* (MWNF) of carbon can be deposited onto inorganic surfaces such as silicon. The MWNFs are ideal for developing nanoscale electrodes since they range in size from 20 to 100 nm in

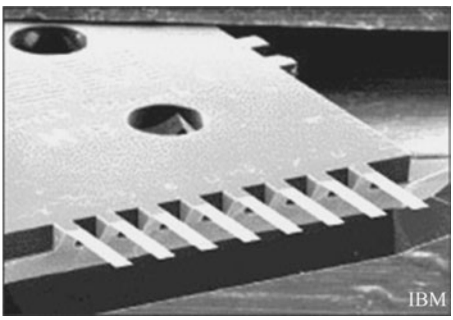


Figure 6.5 DNA MEMS analyzer.

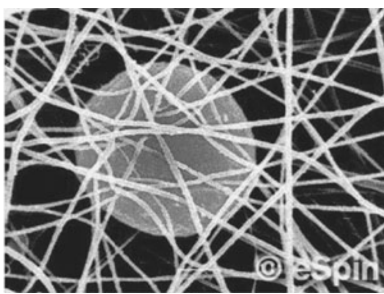


Figure 6.6 CNT filter.

diameter. The electrodes protruding vertically from the substrate can be rigidized by interspatial filling. Ames developed a gap-filling technique where spacing between MWNFs is filled with a dielectric such as SiO_2 or spin-on glass. CVD is also used to deposit SiO_2 followed by chemical mechanical polishing to planarize the top surface. Only the very tips of the MWNFs are exposed while the rest are buried inside the SiO_2. Electrical characterization of these tips indicate that they function as electrodes, as desired, and hence are suitable for attaching DNA or other chemical groups.[2]

6.2.4 Nanomeasurement

While there are committees and conferences on nanopackaging, it is difficult to find any substantive information yet. Nanodevices may not have gone far enough yet to require packaging outside a laboratory environment. Wisely, much of the government funding, especially at NIST, is focusing on measurement. Nanotech has been used for at least 40 years, often on mundane products that were greatly improved by adding nanoparticle carbon black. But the science has only been around for about a decade, marked by the announcement of the *atomic force microscope* (AFM) by IBM. IBM was a pioneer in atomic force microscope development. Binnig and Heinrich Rohrer of IBM's Zurich Lab discovered principles, proposed theories, and finally built equipment that marked the real beginning of nanoscience. They won the Nobel Prize for the scanning probe microscope in 1986. The resulting AFM has since become a critical enabler of the nanotechnology. IBM has licensed many companies who now offer various measuring and manipulating equipment based on atomic forces. The basic patent for the AMF was filed in August 4, 1986 and has been reissued.[3] However, the patent for the scanning tunneling microscope, the predecessor to the AFM, was filed in 1980.[4] This remarkable patent has only 12 claims. The ability to see atoms and molecules, followed by the ability to move them, soon after, really laid the foundation

for strategic nanotechnology. While rubber technologists knew how to make effective carbon black, and realized that the particles were small, it was much later that advances in measurement provided true understanding. Continuous success in measuring devices is essential for product success at the nanoscale.

6.2.5 Nanodevices

There are a variety of nanotechnology classes for materials and devices, and many, if not most devices and subcomponents will need to be packaged. The list in Table 6.1 indicates where nanotechnology is being explored. But at this early stage, much of the work is directed toward understanding principles and phenomenon, not making products. We are mostly at the nanoscience stage that should precede the technology. But products are nevertheless being described. Some will require enclosure type packages and others will just be a subcomponent of a larger system that relies on the packaging of that equipment. It is too early to accurately determine what the packaging needs will be, until programs are moved further along; but device fabrication is progressing rapidly.

While many of the groups in Table 6.1, such as bio, power, and optical, will require packages, our focus will be on nanoelectronics for the remaining.

TABLE 6.1 Nanotechnical Scope

Device of system
Atomic optics
Biosystems
Bose-Einstein condensates
Capacitors
Energy conversion storage
Laser manipulation of atoms; atomic tweezers
Magnetic storage
Nanocolumns
Nanoelectronics
Nanoelectromechanical systems (NEMS)
Nanofluidics
Nanotube plastic composites
Nanopower sources; can be additives
Optical storage
Optics and optical interconnections
Plasma trapping and control; energy related mechanisms
Quantum computers
Quantum dots and related principles
Sensors; discrete and multiple type
Separation
Spectrometer for nanoscale chemical analysis
Thermal devices

6.2.6 Nanoelectronics devices

Carbon nanotubes are the most common and important building blocks of nanotechnology, especially for electronics. They were first discovered in 1991 by Sumio Iijima of NEC.[5] Some suggest that the CNT is a natural evolution of carbon fibers and filaments that were known well over 100 years ago; Hughes and Chambers filed for a patent for manufacturing carbon filaments in 1896.[6] Cavemen likely produced nanoparticles before recorded history. But today, we finally have the ability to visualize and measure bucky balls, CNTs, and other structures.

CNTs have one hundred times the tensile strength of steel, much better thermal conductivity than metals, and electrical conductivity similar to copper. CNTs have the ability to carry much higher currents than metal wires, however. Nanotubes come in a variety of different structures that have different properties: long, short, single-walled, multiwalled, open, closed, with different types of spiral structure, and so on. Carbon nanotubes are effectively long, thin cylinders of graphite. Graphite is made up of layers of carbon atoms arranged in a hexagonal lattice (benzene ring structures) like chicken wire. The theoretical minimum diameter of a carbon nanotube is around 0.4 nm, which is about as long as two silicon atoms side-by-side, and nanotubes this size have been made. Average diameters tend to be around the 1.2-nm mark, depending on the process used to create them. CNT electrical properties make them the leading candidate for nanoelectronics, but no one can tell what the next breakthrough will bring.

Nanopore membrane structures have also been developed at NASA-AMES that could be applied to Bio-MEMS, especially for sensors. Stolc and coworkers[7] have developed a novel nanopore technology. A nanopore of the size 2-3 nm in diameter has been fabricated, although dimensions can be varied. The pore structure can be mounted on a membrane that could be applied to a MEMS structure. The membrane can be used as a filter or sensor. Fluid could be pumped through the pore structure that would show a current if connected as an electrode, provided there were ions in the fluid. In the absence of DNA going through the pore, there is a background current signal due to the transport of ions through the pore in response to the applied electric field across the patch clamp. When a strand of DNA passes through the pore, the background signal would be suppressed due to the blockage. The major challenge of this technology is to generate the right size pores. Further success should yield materials for a variety of MEMS applications, especially in the biomedical field. The electrical sensor area of nanotechnology will require highly specialized packaging.

Hopefully, nanotechnology will become a valuable companion for MEMS with synergy from the respective fields. Now, let us investigate pure nanodevices starting with electronic devices.

Transistors. Transistors have been built using carbon nanotubes that have a semiconductor molecular structure. They behave like one-dimensional quantum wires that can be either metallic or semiconducting, depending on their chirality and diameter. This CNT device can be classified as a *field effect transistor* (FET), or CNTFET. Silicon substrate is first oxidized and a CNT is placed on the resulting SiO_2 layer. This can be done in the lab by spreading CNT solution on the oxide. A gate and source drain contact electrodes which are formed at the correct locations using SEM ATM techniques, certainly not a production-worthy method. The contact metal electrodes can be Ti, Ni, Al, Au, and so on. So far, Ti, which forms metal-carbide bonds with the CNT, gives the lowest contact resistance. The transistors show a *p-type* character, but it is not due to doping in the nanotube, but rather is the result of barriers at the source and drain, or nanotube interfaces. N-type FETs can be produced by treating the device at high temperatures that drive off absorbed oxygen from the source and drain contact regions. The performances of the CNTFETs are comparable to those of the state-of-the art *metal oxide silicon field effect transistors (*MOSFETs).

Many universities, and some of the largest electronics companies in the world, are actively pursuing nanoelectronics, and the transistor is the first step. Estimates for commercial nanotransistors range from a few more years to about fifteen. Some of the electronic giants working on CNT transistors are NEC of Japan, IBM of the United States, and Infinion of Europe. NEC predicts a commercial CNT transistor by the year 2010. They point out that control of CNT electrical properties, and processes to build devices, is not far away. The fabrication process needs considerable refinement too and could change dramatically in the future. Figure 6.7 shows a CNT-based transistor design and Fig. 6.8 shows a function device in a laboratory environment. The NEC researchers were able to control the growth of the CNTs on a silicon substrate by placing a catalyst on top of the substrate which can provide a modest level of control for positioning of the CNT. They are also developing ways of creating connections between electrodes and the CNT. CNT transistor integration will be required if this approach is ever going to replace silicon-based semiconductors.

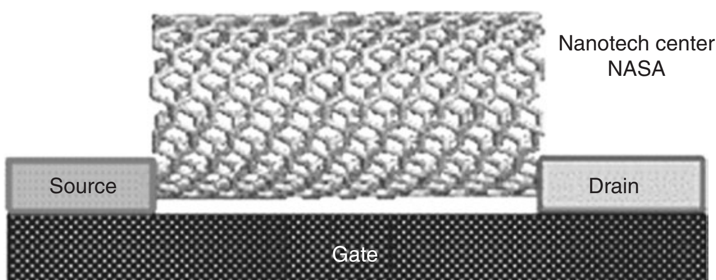


Figure 6.7 CNT nanotransistor design.

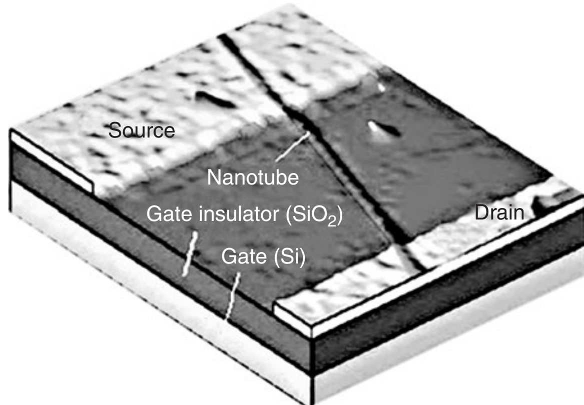


Figure 6.8 CNT nanotransistor–actual. (*Source: Martel, et al., APL, 73: 2447, 1998.*)

One important consideration that will determine some aspects of nanoelectronic packaging is the electrical interconnect to the CNT, or other nanotransistors. Copper is the most common connector in present day electronics and a likely candidate for nanoelectronics. Infinion, is one of the companies that has been intensely investigating CNT connectivity. While they have used e-beam ultrafine lithography, they report that the approach is arduous and time-consuming, and alternative methods are being pursued using standard semiconductor production lithography. One promising method uses plasma etching of narrow Damascene structures in a dielectric and direct etching of narrow metal structures. The Damascene grooves with widths down to 20 nm can be fabricated by using a removable spacer technique with polysilicon as the auxiliary film, and a hard-mask process that was developed for direct etching of narrow metal structures.

They were able to produce a large number of structures with deep sublithographic lateral dimensions across silicon wafers using methods derived from standard processes. One of the most unusual results was experimental evidence for size effects in nanointerconnects. These effects produce a substantial increase in the electrical resistivity of copper lines for lateral dimensions below 100 nm. These results suggest that there will be unforeseen problems at nanoscale. Their experiments pose some important questions about future metallization architecture and scaling methodology. At the very least, design rules will be needed to compensate for the performance gap that appears to be associated with nanotechnology. For example, minimum pitch should only be used for very local interconnects where lengths are short enough to prevent extreme signal retardation.

Infinion is also forging ahead with CNT-IC concepts and believes that CNT transistor integration will be required to make nanoelectronics commercially viable. Infinion is working on both horizontal (in plane) and vertical configurations. CNTs might be grown vertically and then insulators

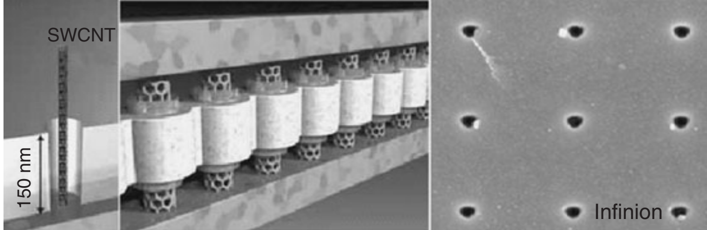


Figure 6.9 Infinion vertical CNT concept.

and connections fabricated around them. Alternatively, a dielectric could be formed with nanovias, and CNTs would be deposited or formed within these cavities. The result would be an array of vertical CNT transistors that are interconnected. If silicon materials are used, the chip would be a hybridization of traditional silicon semiconductor fabrication and carbon-based nanotechnology. The resulting CNT-IC might have a first-level interconnect system similar to the present Si with metal pads. Then, the package would be more conventional. Figure 6.9 shows the Infinion vertical CNT concept.

Optoelectronics. Nanodevices, like the CNT, have been found to emit light when current is reversed—similar to the effect seen with semiconductor light emitting diodes (LEDs). Figure 6.10 shows an artist's conception of a light emitting CNT from the Institute of Electrical and Electronic Engineers (IEEE), which has been devoting a strong effort in covering the topics of nanoelectronics and related areas.

New laser principles have also been discovered that will have commercial application in a relatively short time. Nanowires were found to lase

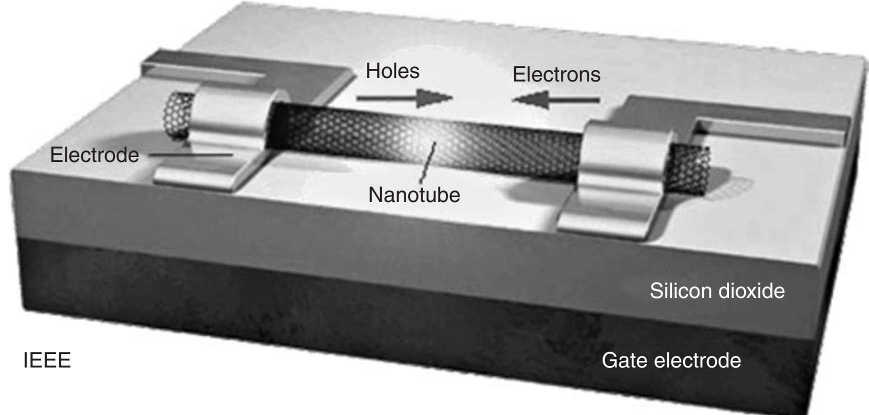


Figure 6.10 CNT light emitter.

when energy was applied; and work is aimed at using the principle for flat panel displays. Figure 6.11 shows nanowires made of zinc oxide. UC – Berkeley is carrying out much of the work in this area and has produced valuable results, including emission of UV light. The nanowires form a natural resonance cavity suitable for lasing without the need for fabricating mirrors. Instead, the wires provide their own mirrors with the interface between the substrate and ZnO serving as one mirror and the perfectly cleaved hexagonal end of the nanowire serving as the other. They lase in different modes between 370- and 400-nm wavelengths. The power source method used is a process called *optical pumping*. The ZnO nanowires were flashed with light from a visible light laser. This light excited the ZnO molecules, causing them to emit photons. The term used by the Berkeley group for this process is "nanowire nanolaser." The UV emitter could be used in a MEMS reactor which utilized photochemistry. Other MEMS applications would be in UV spectrophotomers or bio-MEMS, where UV could assist growth or destroy certain species. However, to be readily applicable, the pumping laser would need to be in the chip-scale range.

CNT-based flat panel displays are also receiving much attention, and electronic giants like Samsung and Philips are active with products already announced. Figure 6.11 shows a CNT-type configuration for flat panel displays and Fig. 6.12 displays a close-up image of closely-spaced grown nanowires.

Triodes. Work at AT&T-Bell Labs led to the discovery of electronic effects at the nanoscale that are usually seen in vacuum triode tubes, but without requiring a vacuum. The effect involves field emission of electrons and extraction of electrons from a solid source by their tunneling through the surface potential barrier. However, Professor Richard Smalley and coworkers did some of the earliest work on field emission from carbon nanotubes.

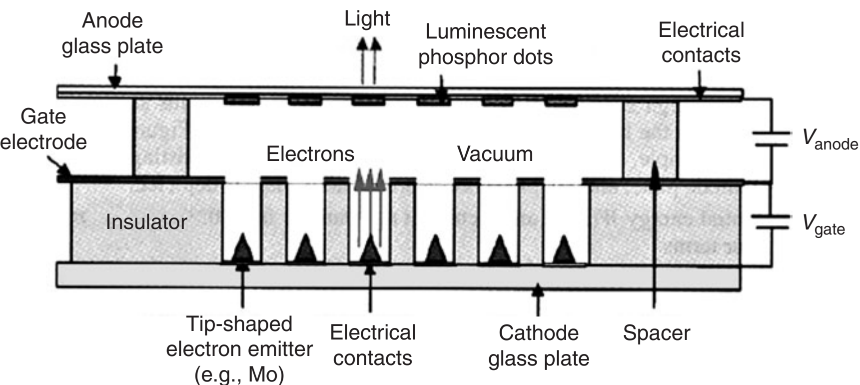
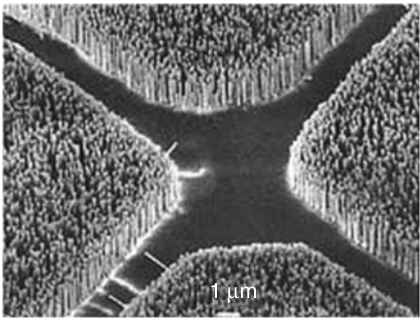


Figure 6.11 CNT flat panel display.



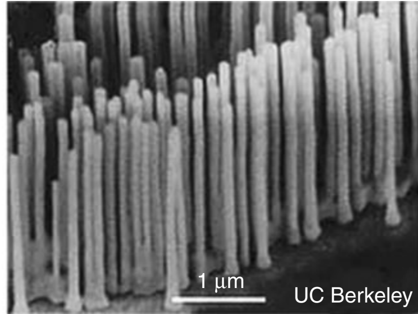


Figure 6.12 Nanowire array.

It was discovered that carbon nanotube films yield very high current densities with minimal extraction potential. CNT applications for field emitters include single electron beam devices; electron microscopes; microwave amplifiers; and multiple electron-beam devices, like flat panel displays, which are covered elsewhere.

Other. Only the most recent, and almost-reduced-to-practice devices have been included; but more are on the way. If MEMS is at an embryonic stage after 25 years, nanotechnology is still a glint in the eyes of would-be creators.

6.2.7 Nanoelectronics plus MEM

We should expect to see some level of merging of nanoelectronic devices with MEMS just the way it appears to be happening with silicon-based electronics. If carbon nanotubes are being combined with silicon or silicon oxide microstructures, then combining CNT-based devices and others with MEMS should also produce useful results. The nanoink pen system may be an example. The *dip-pen nanolithography* (DPN) machine is based on atomic force microscope principles where a tiny arm and tip is manipulated to actually write with ink all the way down to the nanoscale. While the original writer used a single pen, more advanced versions use an array of pens fabricated with MEMS technology. The developers envision a future single chip that is fabricated with over a million electromechanical pens to substantially boost productivity, called the "MEGApede." Figure 6.13 shows a close-up image of the nano-electromechanical systems (NEMS) chip.

6.2.8 Nano enhanced packaging

Throughout the previous chapters, we have worked with concepts, materials, and processes that can successfully and efficiently deliver optimum solutions for the packaging of MEMS and MOEMS devices with their

Figure 6.13 MEGApede from Nanoink, Inc.

assortment of special needs. But, since the mechanical devices require much more design freedom and process versatility, we almost certainly have created the tool set for nanoelectronics packaging.

Packaging fillers now used in encapsulants and underfills can have more useful properties at the nanoscale. Underfills are one example where silica nanopowder has been used to solve a problem.[8] The no-flow underfill process, or the predispensed underfill, or flux method, are attractive alternatives to the capillary underfills in the flip chip. But there has been a limitation for no-flow underfills since added filler interferes with soldering. The solution has been to leave out filler, although this results in high *coefficient of thermal expansion* (CET) compared to that of capillary underfills. Conventional micron-range silica has not been successfully incorporated into no-flow formulations even at lower levels. The silica becomes lodged between the flip chip bumps and *printed circuit board* (PCB) pads, and always interferes with the solder-interconnection process. Now, nanocomposites and no-flow underfill address this problem. Nanosilica fillers can be incorporated into self-fluxing no-flow underfill products to reduce the CTE of the formulation. And unlike conventional fillers, nanosilica filler does not interfere with solder interconnection. This nanocomposite technology has produced underfill that is promising

and has material properties and thermal performance similar to standard capillary products. Thermal cycling data demonstrates a significant reliability enhancement with a nanocomposite no-flow underfill.

6.3 Packaging Nano

We have seen that nanotechnology has already created both passive and active devices. While passive devices, like nanopore filters may be useful as subcomponents for MEMS devices and nanoparticles may be additives for their packages, active devices can be stand-alone systems. Although nanomechanical devices are mostly being used as parts of large machines and may not require discrete packages, the nanoelectronic devices will certainly require individual packaging. Today's electronic packaging designs and technology may possibly serve as a beginning for nanoelectronics, but it is more likely that all of the new designs, concepts, materials, and processes now emerging for MEMS and MOEMS are much more suitable, primarily because of their high level of versatility.

We have spent many pages in this book examining old packaging methods and their applications to MEMS. But, we have also discovered that old materials and processes "come up short" for future applications. We have had to go well beyond conventional electronic packaging to find better solutions. In fact, we have discovered that MEMS needs MEMS-specific packaging that needs to be developed, unless we want to compromise and keep trying to force-fit conventional electronic packaging technology as a shortcut answer. During the journey to find cost-effective solutions for MEMS and MOEMS, we have borrowed from other industries, and also covered novel concepts in order to optimize our MEMS packaging solutions. The higher level of versatility for MEMS solutions will make them applicable to nanoelectronics. While no one is really sure what the requirements will be for nanoelectronics, it is likely that many will be the same as for MEMS. We may speculate, for example, that nanoelectronics transistors will operate better in a cavity style package, and if this is proved, then we have already reviewed the area of lowest cost and highly versatile precision cavity-packaging. We may also have delved into methods that will apply to nano-optoelectronic devices in the search for MOEMS packaging.

Nanoelectronics departs from traditional inorganic semiconductor technology to presently base its devices on organic carbon-based chemistry and physics. Many nanoelectronic devices are centered on CNT and we should assume that some nanoelectronic devices, perhaps most of them that will become commercial, will be CNT-based. This can at least be a starting point presumption for us to begin assessing packaging needs. A CNT electronic device will still require a platform and an electrical interconnect. We do not know exactly what the package requirements will be, but we do not

need to know at this juncture, either. Based on the known properties of CNTs, we could estimate the hermeticity requirements and some of the other criteria. It is quite possible, and even likely, that requirements for nanoelectronic devices will be satisfied by MEMS packaging. The rationale is that we are developing very versatile, easily customized, and cost-effective packaging processes for MEMS. It seems unlikely that nano will add any significant new requirements and may not even be as demanding as MOEMS devices.

While nanoelectronics is being viewed as electronic only, it is probable that mechanical features will be incorporated so that a MEMS-like area will evolve. We can call this "NEMS," but we will need to define this term, and here is the issue: Today, we have the process capability to produce MEMS devices that fall into the nano-size domain of 1 m to 100 nm. However, electronics is already below 100 nm (90-nm node) and heading for 65 nm and smaller feature sizes in a few years according to various roadmaps. But we are not calling it nanoelectronics, nor should we. The nanoelectronics term is being reserved for nonclassical devices based nanostructures like the CNT. We should use the same strategy for MEMS, and not confuse the nanotechnology terms even more than has already been done by using a size-only criterion. NEMS should be made with components that fit nanotechnology, such as the nanomotors that have been reported. But from the packaging perspective, the terminology will not matter since the successful packages will meet the requirements for the devices no matter what they are called.

6.4 Summary, Conclusions, and the Future

MEMS is just reaching its second wave of development, "new MEMS," while nano is mainly theoretical and is in a science-under-development mode. Although the definition of nanotechnology is still being debated, a large cast of researchers and developers is forging ahead. Nanomaterials are already being used in many products, including electronic packaging systems. Nanoscience, scarcely a decade old, has been moving quickly to deliver the tools to see, manipulate, and measure the materials, devices and phenomenon. Nanoelectronics is mostly still on the drawing board or in artistic renderings, but all of the important principles needed to build technology have been demonstrated. Nano-optics is also moving ahead as nanotechnology criss-crosses all sciences. While almost nothing of substance is being reported in the area of packaging for nano, considerable nanoelectronic device success is being announced as laboratories around the world apply talent and expertise. But the lab devices will soon emerge into the commercial world in need of packaging. MEMS and MOEMS packaging technology will become the basis for nanodevice packaging in the not-too-distant future.

References

1. Drexler, E.K., *Engines of Creation*, Anchor Book, New York, NY, 1986.
2. Li, J., R. Stevens, L. Delzeit, H. T. Ng, A. Cassell, J. Han, and M. Meyyappan, "Electronic Properties of Multiwalled Carbon Nanotubes in an Embedded Vertical Array," *Appl. Phys. Lett.*, Vol. 81, No. 5, pp. 910–912, 2002.
3. Bennig, G. K., "Atomic Force Microscope and Method for Imaging Surfaces with Atomic Resolution," U.S. Patent 4,724,318, February 9, 1988.
4. Binnig, G., and H. Rohrer, "Scanning Tunneling Microscope," U.S. Patent 4,343,993, August 10, 1982.
5. Iijima, S., "Helical Microtubules of Graphitic Carbon," *Nature*, Vol. 354, No. 6348, pp. 56–58, November 1991.
6. Hughes, T., and C. Chambers, "Method of Manufacturing Carbon Filaments," U.S. Patent 405,480, June 18, 1889.
7. Meyyappan, M., et al., *Nano and BioTechnology Research at NASA Ames*, NASA Ames Research Center, Moffett Field, CA, Revised: December 17, 2002.
8. Gross, K., S. Hackett, W. Schultz, and W. Thompson, "Nanocomposite Underfills for Flip-Chip Applications," *Electronic Components and Technology Conference, 53rd Proceedings*, May 27–30, 2003, pp. 951–956.

Bibliography

Aberson, et al., "Novel Backend Singulation Techniques to Enable Commercialization of Optical MEMS," *Proceedings of the International Conference on MEMS, NANO and Smart Systems* (*ICMENS'03*), p. 131, Banff, AB, Canada, July 2003.

Akbar, M., and M. A Shanblatt, "A Fully Integrated Temperature Compensation Technique for Piezoresistive Pressure Sensor," *IEEE Trans. Electron Devices*, Vol. 42, No. 3, pp. 771–775, 1993.

Alley, R. L., G. J. Cuan, R. T. Howe, and K. Komvopoulos, "The Effect of Release-Etch Processing on Surface Microstructure Stiction," *Technical Digest of the 1992 IEEE Solid-State Sensor and Actuator Workshop*, Hilton Head Island, SC, pp. 202–207, 1992.

Analog Devices, Inc., "Analog Devices' New Accelerometer Opens Cost-Sensitive Market Opportunities for MEMS Technology," Press Release, January 29, 2003. Available at http://www.analog.com/en/press/

Ando, D., K. Oishi, T. Nakamura, and S. Umeda, "Glass Direct Bonding Technology for Hermetic Seal Package," *Proceedings of IEEE MEMS'97*, pp. 186–190, Nagoya, Japan, 1997.

Awatani, et al., "Damage Free Dicing Method for MEMS Devices," *International Conference on Optical MEMS*, *Conference Digest 2002 IEEE/LEOS*, pp. 137–138, Lugano, Switzerland, August 2002.

Barker, S., and G. M. Rebeiz, "Distributed MEMS True-Time Delay Phase Shifters and Wide-Band Switches," *IEEE Trans. Microwave Theory Tech.*, Vol. 46, pp. 1881–1890, April 1998.

Barnes, S. M., S. L. Miller, M. S. Rodgers, and F. Bitsie, "Torsional Ratcheting Actuating System," *International Conference on Modeling and Simulation of Microsystems*, pp. 273–276, San Diego, CA, March 2000.

Bartek, M., et al., "Vacuum Sealing of Microcavities Using Metal Evaporation," *Sens. Actuators*, Vol. 61, pp. 364–368, 1997.

Bernstein, J., "An Overview of MEMS Inertial Sensing Technology," *Sensors*, Vol. 20, No. 2, February 2003.

Bitko, G., D. J. Monk, T. Maudie, D. Stanerson, J. Wertz, J. Matkin, and S. Petrovic, "Analytical Techniques for Examining Reliability and Failure Mechanisms of Barrier Coating Encapsulated Silicon Pressure Sensors Exposed to Harsh Media," *Micromachining and Microfabrication '96 Symposium: Micromachined Devices and Components II*, pp. 248–258, SPIE, Austin, TX, 1996.

Bossche, A., C. V. B. Cotofana, and J. R. Mollinger, "MEMS Packaging: State of the Art and Future Trends," *Proceedings of the SPIE—The International Society for Optical Engineering*, Vol. 3328, pp. 166–173, San Diego, CA, 1998.

Bratter, R. L., "Commercial Success in the MEMS Marketplace," *Optical MEMS, 2000 IEEE/LEOS International Conference*, pp. 29–30, Kauai, HI, 2000.

Brown, N., "New Generation CTD Sensor Systems," *IEEE OCEANS*, Vol. 19, pp. 280–286, 1987.

Brown, S., J. Gilbert, H. Guckel, R. Howe, G. Johnson, P. Krulevich, and C. Muhlstein, "Microelectromechanical Systems for Materials Research," *Mater. Res. Soc.*, Vol. 518, 1998.

Brown, S., C. Muhlstein, and W. VanArsdell, "Materials Reliability in MEMS Devices," *Proceedings of the International Conference on Solid-State Sensors and Actuators, Transducers 97*, Chicago, pp. 591–593, 1997.

Bryzek, J., K. Petersen, and W. McCulley, "Micromachines on the March," *IEEE Spectrum Mag.*, Vol. 31, No. 5, pp. 20–31, May 1994.

Bugnacki, M., J. Pyle, and P. Emerald, "A Micromachined Thermal Accelerometer for Motion, Inclination, and Vibration Measurement," *Sensors*, Vol. 18, No. 6, June 2001.

Copyright © 2005 by The McGraw-Hill Companies, Inc. Click here for terms of use.

Burns, D. J., and H. F. Helbig, "A System for Automatic Electrical and Optical Characterization of Microelectromechanical Devices," *JMEMS*, Vol. 8, No. 4, pp. 473–481, December 1999.

Busta, H. H., "Vacuum Microelectronics—1992," *J. Micromech. Microeng.*, Vol. 2, pp. 43–74, 1992.

Caillat, P., and G. Nicolas, "Fluxless Flip-Chip Technology," *1st International FlipChip Symposium*, San Jose, CA, February 1994.

Chang, K., *Handbook of Microwave and Optical Components*, Vol. 1, Wiley, New York, 1989.

Chavan, A. V., and K. D. Wise, "Batch-Processed Vacuum Sealed Capacitive Pressure Sensors," *JMEMS*, Vol. 10, No. 4, pp. 580–588, 2001.

Chen, A., R. Luo, T. C. Tan, and C. C. Liu, "A Thick-Film Calorimetric Sensor for Monitoring the Concentration of Combustible Gases," *Sens. Actuators*, Vol. 19, pp. 237–248, 1989.

Cheng, Y. T., L. Lin, and K. Najafi, "Localized Silicon Fusion and Eutectic Bonding for MEMS Fabrication and Packaging," *IEEE/ASME JMEMS*, Vol. 9, pp. 3–8, March 2000.

Cheng, Y. T., L. Lin, and K. Najafi, "Localized Bonding with PSG or Indium Solder as Intermediate Layer," *Proceedings of IEEE Micro Electro Mechanical Systems Workshop*, pp. 285–289, Orlando, FL, January 1999.

Cheng, Y. T., L. Lin, and K. Najafi, "Fabrication and Hermeticity Testing of a Glass-Silicon Package Formed Using Localized Aluminum/Silicon-to-Glass Bonding," *Proceedings of IEEE Micro Electro Mechanical Systems Workshop*, pp. 757–762, Miyazaki, Japan, January 2000.

Chiao, J. C., and D. B. Rutledge, "Microswitch Beam-Steering Grid," *Proceedings of International Conference Millimeter Submillimeter Waves Application*, San Diego, CA, January 1994.

Chiao, M., and L. Lin, "Hermetic Wafer Bonding Based on Rapid Thermal Annealing," *Proceedings of the Solid-State Sensor and Actuator Workshop*, pp. 347–350, Hilton Head Island, SC, June 2000.

Chin, S., "Fairchild's MEMS Push Seeks to Energize Market," *Electronic Buyer's News*, October 2001.

Chiou, J. A., "Simulations for Thermal Warpage and Pressure Nonlinearity of Monolithic CMOS Pressure Sensors," *IEEE Trans. Adv. Packag.*, Vol. 26, No. 3, pp. 327–333, 2003.

Cho, S., and F. M. Erdmann, "An On-Chip Hermetic Packaging Technology for Micromechanical Devices," *Solid-State Sensor and Actuator Workshop*, pp. 229–232, Hilton Head Island, SC, June 1998.

Chomas, L. C., et al., "Low-Cost Manufacturing/Packaging Process for MEMS Inertial Sensors," *Proceedings of the 36th International Symposium on Microelectronics* (*IMAPS 2003*), Boston, MA, November 2003.

Clark, S. K., and K. D. Wise, "Pressure Sensitivity in Anisotropically Etched Thin-Diaphragm Pressure Sensors," *IEEE Trans. Electron Devices*, Vol. 26, No. 12, pp. 1887–1895, 1979.

Clark, W., R. Howe, and R. Horowitz, "Surfacemicromachined Z-Axis Vibratory Rate Gyroscope," *Proceedings of the Solid-State Sensor and Actuator Workshop*, pp. 283–287, Hilton Head Island, SC, 1996.

Cohn., et al., "MEMS Packaging on a Budget (Fiscal and Thermal)," *Proceedings of the 9th International Conference on Electronics, Circuits and Systems*, Vol. 1, pp. 287–290, Dubrovnik, Croatia, September 2002.

Cohn, M. B., Y. Lang, R. T. Howe, and A. P. Pisano, "Wafer-to-Wafer Transfer of Microstructures for Vacuum Packaging," *Proceedings of the Solid-State Sensors and Actuators Workshop*, Hilton Head Island, SC, pp. 32–35, June 1996.

Core, T. A., W. K. Tsang, and S. J. Sherman, "Fabrication Technology for an Integrated Surface-Micromachined Sensor," *Solid State Technol.*, pp. 39–47, October 1993.

deBoer, M. P., P. J. Clews, B. K. Smith, and T. A. Michalske, "Adhesion of Polysilicon Microbeams in Controlled Humidity Ambients," *Mater. Res. Soc. Proc.* Vol. 518, 1998.

deBoer, M. P., J. M. Redmond, and T. A. Michalske, "A Hinged-Pad Test Structure for Sliding Friction Measurement in Micromachinig," *SPIE*, Vol. 3512, Santa Clara, CA, September 1998.

deLambilly, H., "MEMS Packaging: More Precise, Faster, Cheaper—A Challenge," *Proceedings of the Sensors Expo.*, pp. 173–179, Boston, MA, 1997.

deMoor, P., et al., "Low Temperature Zero-Level Hermetic Packaging for MEMS Based on Solder and Polymer Bonding," *IMAPS 5th Topical Workshop on MEMS*, *Related Microsystems and Nanopackaging*, Boston, MA, November 2003.

deMoor, P., et al., "Hermetically Sealed On-Chip Packaging of MEMS Devices," *Proceedings of the European Space Components Conference (ESCCON)*, pp. 67–69, Noordwijk, The Netherlands, March 2000.

deMoor, P., et al., "Process Development of Fast and Sensitive PolySiGe Microbolometer Arrays," *Photodetectors:Materials and Devices VI., SPIE Proceedings 2001*, Vol. 4288, pp. 94–100, Bellingham, WA, 2001.

deMoor, P., S. Sedky, D. Sabuncuoglu, and C. VanHoof, "Uncooled IR Bolometers Using Surface Micromachined PolySiGe," *Proceedings of 2nd International Integrated Micronanotechnol. Space Applicat. Conference*, pp. 43–46, Pasadena, CA, April 1999.

Eaton, W., and J. Smith, "Planar Surface-Micromachined Pressure Sensor With a Subsurface, Embedded Reference Pressure Cavity," *SPIE Micromachined Devices and Components II*, Vol. 2882, pp. 271–277, 1996.

Eherhardt, J. J., L. Colin, A. Accorsi, M. Kazmierczak, and I. Zdanevitch, "Catalytic Oxidation of Methane on Platinum Thin Film," *Sens. Actuators B*, Vol. 7, pp. 656–660, 1992.

Elderstig, H., and P. Wallgren, "Spin Deposition of Polymers Over Holes and Cavities," *Sens. Actuators*, Vol. 46–47, pp. 95–97, 1995.

Eriksen, G. F., and K. Dyrbye, "Protective Coatings in Harsh Environments," *J. Micromech. Microeng.*, Vol. 6, pp. 55–57, 1996.

Esashi, M., S. Shoji, and A. Nakano, "Normally Closed Microvalve and Micropump Fabricated on a Silicon Wafer," *Proceedings of the IEEE* Micro Electro Mechanical Systems, pp. 29–34, Salt Lake City, UT, February 1989.

Estes, R. H., "Technology Assessment: PFC® Polymer Flip Chip Solderless Bump Process," *Epoxy Technol. Tech. Paper GB-31*, Billerica, MA.

Farrell, B., et al., "The Liquid Crystal Polymer Packaging Solution," *Proceedings of the IMAPS 2003 International Symposium*, pp 18–23, Boston, MA, November 2003.

Field, L. A., R. M. White, and A. P. Pisano, "Fluid Powered Rotary Gears and Micro-Flow Channels," *Proceedings of the 6th International Conference on Solid-State Sens. Actuators (Transducers'91)*, pp. 1033–1036, San Francisco, CA, 1991.

Firth, J. G., A. Jones, and T. A. Jones, "The Principles of the Detection of Flammable Atmospheres by Catalytic Devices," *Combustion and Flame*, Vol. 21, pp. 303–311, 1973.

Firth, J. G., "Measurement of Flammable Gases and Vapours," in: C. F. Cullis and J. G. Firth, eds., *Detection and Measurement of Hazardous Gases*, Heinemann, London, 1981.

Fleming, J., and C. Barron, "Novel Silicon Fabrication Process for High-Aspect-Ratio Micromachined Parts," *Proceedings of the SPIE Micromachining and Microfabrication Process Technology*, Vol. 2639, pp. 1033–1036, Austin, TX, 1995.

Frank, R., M. L. Kniffin, and L. Ristic, "Packaging for Sensors," in: L. Ristic, ed., *Sensor Technology and Devices*, pp. 203–238, Artech House, Boston, MA, 1994.

Freeman, D. M., A. J. Aranyosi, M. J. Gordon, and S. S. Hong, "Multidimensional Motion Analysis of MEMS Using Computer Microvision," *Proceedings of the Solid-State Sensor and Actuator Workshop*, pp. 150–155, Hilton Head Island, SC, June 1998.

Fujita, T., K. Hatano, K. Maenaka, T. Mizuno, T. Matsuoka, T. Kojima, T. Oshima, and M. Maeda, "Vacuum Sealed Silicon Bulk Micromachined Gyroscopes," *Proceedings of the 10th International Solid-State Sens. Actuators Conference*, pp. 914–917, Sendai, Japan, 1999.

Fullin, E., J. Gobet, H. A. C. Tilmans, and J. Bergqvist, "A New Basic Technology for Magnetic Micro-Actuators," *Proceedings of the IEEE MEMS'98*, pp. 143–147, Heidelberg, Germany, 1998.

Garcia, E. J., and J. J. Sniegowski, "Surface Micromachined Microengine," *Sens. Actuators A*, Vol. 48, p. 203, 1995.

Garcia, E. J., and J. J Sniegowski, "Surface Micromachined Microengine as the Driver for Micromechanical Gears," *Proceedings of the 8th International Conference on Solid-State Sensors and Actuators and Eurosensors IX*, pp. 365–368, Stockholm, Sweden, June 1995.

Gobet, J., F. Cardot, J. Bergqvist, and F. Rudolf, "Electrodeposition of 3D Microstructures on Silicon," *J. Micromech. Microeng.*, Vol. 3, pp. 123–130, 1993.

Goldsmith, C., J. Randall, S. Eshelman, T. H. Lin, D. Denniston, S. Chen, and B. Norvell, "Characteristics of Micromachined Switches at Microwave Frequencies," *IEEE MTT-S Symp. Dig.*, pp. 1141–1144, June 1996.

Guckel, H., and D. Burns, "Planar Processed Polysilicon Sealed Cavities for Pressure Transducer Arrays," *IEDM*, pp. 223–225, 1984.

Guckel, H., "Surface Micromachined Pressure Transducers," *Sens. Actuators*, Vol. 28, pp. 133–146, 1991.

Gui, C., H. Albers, J. G. E. Gardeniers, M. Elwenspoek, and P. V. Lambeck, "Fusion Bonding of Rough Surfaces with Polishing Technique for Silicon Micromachining," *Microsyst. Technol.*, Vol. 3, pp. 122–128, 1997.

Heschel, M., J. F. Kuhmann, S. Bouwstra, and M. Amskov, "Stacking Technology for a Space Constrained Microsystem," *Proceedings of the IEEE MEMS'98* pp. 312–331, Heidelberg, Germany, 1998.

Hicks, D., S. C. Chang, M. W. Putty, and D. S. Eddy, "Piezoelectrically Activated Resonant Bridge Microacceleromenter," *Proceedings of the Solid-State Sensors and Actuators Workshop*, pp. 225–228, Hilton Head Island, SC, 1994.

R. R. Higashi, et al., "Integrated Silicon Vacuum Micropackage for Infrared Devices," U.S. Patent No. 5,895,233, April, 1999.

Houston, M. R., R. Maboudian, and R. T. Howe, "Self-Assembled Monolayer Film as Durable Anti-Stiction Coatings for Polysilicon Microstructures," *Proceedings of the Solid-State Sensor and Actuator Workshop*, pp. 42–47, Hilton Head Island, SC, June 1996.

Howe, R., "Polysilicon Integrated Microsystems: Technologies and Applications," *Proc. Transducers*, Vol. 1, pp. 43–46, 1995.

Hughes, H., "Semiconductor Wafer Level Package," U.S. Patent No. 5,323,051, 1994.

Ikeda, K. and H. Kuwayama, et al., "Silicon Pressure Sensor with Resonant Strain Gages Built into Diaphragm," *Digest of the 7th Sensor Symposium*, pp. 55–58, 1988.

Ikeda, K., H. Kuwayama, T. Kobayashi, T. Watanabe, T. Nishikawa, T. Oshida, and K. Harada, "Three-Dimensional Micromachining of Silicon Pressure Sensor Integrating Resonant Strain Gauge on Diaphragm," *Sens. Actuators*, Vol. 21–23, pp. 1007–1010, 1990.

Infineon Technologies, *Semiconductor Sensors*, *Data Book*, IEEE, New York, NY, 1999.

Ishihara, T., K. Suzuki, S. Suwazono, M. Hirata, and H. Tanigawa, "CMOS Integrated Silicon Pressure Sensor," *J. Solid State Circuits*, Vol. 22, No. 2, pp. 151–156, 1987.

Jones, E., "The Pellistor Catalytic Gas Sensor," in: P. T. Moseley, and B.C. Tofield, eds., *Solid State Gas Sensors*, A. Higler, Bristol, 1987.

Jourdain, et al., "Investigation of the Hermeticity of BCB-Sealed Cavities for Housing RF MEMS Devices," *MEMS 2002 IEEE International Conference*, Las Vegas, NV, pp. 677–80, 2002.

Juneau, T., and A. Pisano, "Micromachined, Dual-Inputaxis, Angular Rate Sensor," *Proceedings of the Solid-State Sensor and Actuator Workshop*, pp. 299–302, Hilton Head Island, SC, 1996.

Kanda, Y., "A Graphical Representation of the Piezoresistance Coefficients in Silicon," *IEEE Trans. Electron Devices*, Vol. 29, No. 1, pp. 64–70, 1982.

Kang, J. W., and K. Simonette, "Surface Micromachined Multi-Layer Moving Gate Field Effect Transistor (MOGFET) Pressure Switch with Integrated Vacuum Sealed Cavity," *Proceedings of the IEEE MEMS'99*, pp. 499–504, Orlando, FL, 1999.

Kao, et al., "Method and Apparatus for Singulation of Micro-Electro-Mechanical Systems," U.S. Patent No. 5,923, 995, 1999.

Katehi, L. P. B., and G. M. Rebeiz, "Novel Micromachined Approaches to MMIC's Using Low-Parasitic, High-Performance Transmission Media and Environments," *IEEE MTT-S Symp. Dig.*, Vol. 2, pp. 1145–1148, June 1996.

Kim, B. H., and T. D. Chung, et al., "A New Organic Modifier for Anti-Stiction," *JMEMS*, Vol. 10, No. 1, pp. 33–40, 2001.

Klanna, P. K., S. K. Bhatnagar, and W. Gust, "Analysis of Packaging and Sealing Techniques for Microelectronic Modules and Recent Advances," *Microelectron. Int.*, Vol. 16, No. 2, pp. 8–12, 1999.

Kniffin, M., and M. Shah, "Packaging for Silicon Micromachined Accelerometer," *Int. J. Microcirc. Electr. Pack.*, Vol. 19, No. 1, pp. 75–86, 1996.

Ko, W. H., "Packaging of Microfabricated Devices and Systems," *Matls. Chem. Phys.*, Vol. 42, pp. 169–175, 1995.

Koester, D., R. Majedevan, A. Shishkoff, and K. Marcus, *Multi-User MEMS Processes (MUMPS) Introduction and Design Rules*, MCNC MEMS Technology Applications Center, Research Triangle Park, NC, July 1996.

Koopman, N., and S. Nangalia, "Fluxless Flip Chip Joining," *Proceedings of the NEPCON WEST*, Vol. 2, pp. 919–931, Anaheim, CA, 1995.

Kovacs, G. T. A., *Micromachined Transducers Sourcebook*, McGraw-Hill, New York, 1998.

Kroebel, W., "A New Type of Pressure Sensor for Very Fast Measurements in Fast CTD Probes," *IEEE OCEANS*, Vol. 19, pp. 331–334, 1987.

Kuehnel, W., and S. Sherman, "A Surface Micromachined Silicon Accelerometer with On-Chip Detection Circuitry," *Sens. Actuators A*, Vol. 45, No. 1, pp. 7–16, 1994.

Kuhmann, J. F., "Flip-Chip Bonding Investigations on the Self-Alignment of Tin-Lead Bumps Under Vacuum Conditions," *Proceedings of the EuPac'96*, pp. 37–40, Essen, Germany, 1996.

Lau, J., *Flip Chip Technologies*, McGraw-Hill, New York, 1996.

LaVigne, G. F., and S. L. Miller, "A Performance Analysis System for MEMS using Automated Imaging Methods," *Proceedings of the IEEE International Test Conference*, pp. 442–447, Washington, DC, October 1998.

Lee, J. J., D. Atkinson, J. J. Lam, L. Hackett, R. Lohr, L. Larson, R. Loo, M. Matloubian, G. Tangonon, H. DeLosSantos, and R. Brunner, "MEMS Antenna Systems: Concepts, Design, and System Implications," *National Radio Science Meeting*, Boulder, CO, 1996.

Lee, Y. C., A. Parviz, J. A Chiou, and S. Chen, "Packaging for Microelectromechanical and Nanomechanical Systems," *IEEE Trans. Adv. Packag.*, Vol. 26, No. 3, pp. 217–226, 2003.

Legtenberg, R., E. Berenschot, M. Elwenspoek, and J. Fluitman, "Electrostatic Microactuators with Integrated Gear Linkages for Mechanical Power Transmission," *Proceedings of the IEEE MicroElectroMechanicalSystems*, pp. 204–209, San Diego, CA, 1996.

Legtenberg, R., and H. A. C. Tilmans, "Electrostatically Driven Vacuum-Encapsulated Polysilicon Resonators, Part I: Design and Fabrication," *Sens. Actuators*, Vol. 45, pp. 57–66, 1994.

Legtenberg, R., and S. Bouwstra, "Resonating Microbridge Mass Flow Sensor with Low-Temperature Glass-Bonded Cap Wafer," *Sens. Actuators*, Vol. 25–27, pp. 723–727, 1991.

Lemkin, M., B. Boser, and D. Auslander, "A Fully Differential Sigma-Delta Accelerometer with Drift Cancellation Circuitry," *Proceedings of the Solid-State Sensor and Actuator Workshop*, pp. 90–93, Hilton Head Island, SC, 1996.

Leung, A. M., J. Jones, E. Czyzewska, J. Chen, and B. Woods, "Micromachined Accelerometer Based on Convection Heat Transfer," *Proceedings of the IEEE*, pp. 627–630, Heidelberg, Germany, 1998.

Lin, L., "Selective Encapsulation of MEMS: Microchannnels, Needles, Resonators, and Electromechanical Filters," Ph.D. Thesis, UC Berkeley, 1993.

Lin, L., R. T. Howe, and A. P. Pisano, "Microelectromechanical Filters for Signal Processing," *IEEE/ASME JMEMS*, Vol. 7, pp. 286–294, September 1998.

Lin, L., Y. T. Cheng, and K. Najafi, "Formation of Silicon-Gold Eutectic Bond Using Localized Heating Method," Jpn. J. Appl. Phys., Part II, Vol. 11B, pp. 1412–1414, November 1998.

Liu, C., and Y. C. Tai, "Studies on the Sealing of Surface Micromachined Cavities Using Chemical Vapor Deposition Materials," *Proceedings of the Solid-State Sensorsand Actuators Workshop*, pp. 103–106, Hilton Head Island, SC, 1994.

Maboudian, R., "Anti-Stiction Coatings for Surface Micromachines," *SPIE*, Vol. 3511, pp. 108–113, 1998.

Maboudian, R., "Self-Assembled Monolayers as Anti-Stiction Coatings for Surface Microstructures," *Digest of Technical Papers*, *10th International Conference on Solid-State* Sensors and Actuators *(Transducer'99)*, Vol. 1, pp. 22–25, Sendai, Japan, 1999.

Maciossek, A., B. Löchl, H. J. Quenzer, B. Wagner, S. Schulze, and J. Noetzel, "Galvanoplating and Sacrificial Layers for Surface Micromachining," *Microelectron. Eng.*, Vol. 27, pp. 503–508, 1995.

Mack, S., H. Baumann, and U. Gösele, "Gas Tightness of Cavities Sealed by Silicon Wafer Bonding," *Proceedings of the IEEE MEMS'97*, pp. 488–493, Nagoya, Japan, 1997.

Madou, M., *Fundamentals of Microfabrication*, CRC Press, Boca Raton, New York, 2002.

Mailloux, R. J., *Phased Array Antenna Handbook*, Sec. 5.3., Artech House, Norwood, MA, 1994.

Mallon, J., J. Bryzek, J. Ramsey, G. Tomblin, and F. Pourahmadi, "Low-Cost High Volume Packaging Techniques for Silicon Sensors and Actuators," *Technical Digest*, *3rd IEEE Solid-State Sensor and Actuator Workshop*, pp. 123–124, 1988.

Malshe, A. P., C. O'Neal, S. B. Singh, W. D. Brown, W. P. Eaton, and W. M. Miller, "Challenges in the Packaging of MEMS," *Int. J. Microcircuits Electron.Packaging*, Vol. 22, No. 3, pp. 233–241, 1999.

Maluf, N., *An Introduction to Micromechanical Systems Engineering*, Artech House, Boston, MA, 2000.

Man, P. F., B. P. Gogoi, and C. H. Mastrangelo, "Elimination of Post-Release Adhesion in Microstructures Using Conformal Fluorocarbon Coatings," *IEEE JMEMS*, Vol. 6, No. 1, pp. 25–34, January 1997.

Manginell, R. P., J. Smith, A. J. Ricco, D. J. Moreno, R. Hughes, R. Huber, and S. D. Senturia, "Selective, Pulsed CVD of Platinum on Microfilament Gas Sensors," *Proceedings of the Solid-State Sensor and Actuator Workshop*, pp. 23–27, Hilton Head Island, SC, 1996.

Marinis, T. F. and J. W. Soucy, "Vacuum Packaging of MEMS Inertial Sensors," *Proceedings of the IMAPS 2003 International Symposium*, pp. 386–391, Boston, MA, November 2003.

Mastrangelo, C., "Thermal Applications of Microbridges," Ph.D. Thesis, UC Berkeley, 1991.

Mastrangelo, C. and R. Muller, "A Constant-Temperature Gas Flow Meter with a Silicon Micromachined Package," *Proceedings of the Solid-State Sensor and Actuator Workshop*, pp. 43–46, Hilton Head Island, SC, 1988.

Maudie, T., "Testing Requirements and Reliability Issues Encountered with Micromachined Structures," *Proceedings of the 2nd International Symposium on Microstructures and Microfabricated Systems*, pp. 223–230, Chicago, IL, 1995.

Maudie, T., and J. Wertz, "Semiconductor Sensor Performance and Reliability for the Appliance Industry," *Proceedings of the International Appliance Technical Conference*, Champaign, IL, 1995.

Maudie, T., D. J. Monk, D. Zehrbach, and D. Stanerson, "Sensor Media Compatibility: Issues and Answers," *Sensors Expo*, pp. 215–229, Anaheim, CA, 1996.

Maurer, D. J., "Pressure Transducer with Media Isolation and Negative Pressure Measuring Capability," U.S. Patent No. 5,483,994, January 1996.

Miller, S. L., J. J. Sniegowski, G. LaVigne, and P. J. McWhorter, "Friction in Surface Micromachined Microengines," *Proceedings of the SPIE Smart Electronics and MEMS*, Vol. 2722, pp. 197–204, San Diego, CA, February 1996.

Minami, K., T. Moriuchi, and M. Esashi, "Cavity Pressure Control for Critical Damping of Packaged Micromechanical Devices," *Proceedings of the 8th International Solid-State Sens. Actuators Conference*, pp. 240–243, Stockholm, Sweden, 1995.

Mizra, A. R. and A. A. Ayon, "Silicon Wafer Bonding: Key to MEMS High-Volume Manufacturing," *Sensors*, Vol. 20, No. 12, pp. 24–30, 32–33, December 1998.

Monk, D. J., T. Maudie, D. Stanerson, J. Wertz, G. Bitko, J. Matkin, and S. Petrovic, "Media Compatible Packaging and Environmental Testing of Barrier Coating Encapsulated Silicon Pressure Sensors," *Proceedings of the Solid-State Sens. Actuators Workshop*, pp. 36–41, Hilton Head Island, SC, 1996.

Monk, D. J., and M. Shah, "Thin Film Polymer Stress Measurement Using Piezoresistive Anisotropically Etched Pressure Sensors," *Materials Research Society Symposium Proceedings*, pp. 103–109, San Francisco, CA, 1995.

Monk, D. J., Y. Cruz, C. Lopez, T. Maudie, D. Stanerson, and S. Petrovic, "Dielectric Properties of Gels Used for Pressure Sensor Encapsulation," *Corrosion and Reliability of Electronic Materials and Devices*, in: Comizzoli R. B., Frankenthal, R. P., and Sinclair, J. D. editors, pp. 137–149, The Electrochemical Society, Pennington, NJ, 1999.

Mulhern, G. T., D. S. Soane, and R. G. Howe, "Supercritical Carbon Dioxide Drying for Microstructures," *Proceedings of the 7th International Conference on Solid-State Sensors and Actuators*, *Transducers'93*, pp. 296–299, Yokohama, Japan, 1993.

Muhlstein, C. L., S. B. Brown, and R. O. Ritchie, "High-Cycle Fatigue of Polycrystalline Silicon Thin Films in Laboratory Air," *MRS Symposium Proceedings*, San Francisco, CA, 2000.

Muhlstein, C. L., S. B. Brown, and R. O. Ritchie, "High-Cycle Fatigue and Durability of Polycrystalline Silicon Thin Films in Ambient Air," *Sensors Actuator A-Phys.*, Vol. 94, pp. 177–188, 2001.

Muhlstein, C. L., S. B. Brown, and R. O. Ritchie, "High-Cycle Fatigue of Single Crystal Silicon Thin Films," *J. Microelectromechanical Systems*, Vol. 10, No. 4, pp. 593–600, 2001.

Muhlstein, C. L., E. A. Stach, and R. O. Ritchie, "Mechanism of Fatigue in Micron-Scale Films of Polycrystalline Silicon for Microelectromech. S.," *Appl. Phys. Lett.*, Vol. 80, No. 9, pp. 1532–1534, March 2002.

Muhlstein, C. L., E. A. Stach, and R. O. Ritchie, "A Reaction-Layer Mechanism for the Delayed Failure of Micron-Scale Polycrystalline Silicon Structural Films Subjected to High-Cycle Fatigue Loading," *Acta Materialia*, Vol. 50, pp. 3579–3595, 2002.

Muhlstein, C. O., and R. O. Ritchie, "High-Cycle Fatigue of Micron-Scale Polycrystalline Silicon Films: Fracture Mechanics Analysis of the Role of the Silicon/Silica Interface," *Int. J. Fracture*, Vol. 119–120, pp. 449–474, 2003.

Muhlstein, C. L., E. A. Stach, and R. O. Ritchie, "High-Cycle Fatigue Failure of Micron-Scale Polycrystalline Silicon Films for MEMS," *DOE Review Poster*, 2002.

Muhlstein, C. L., and S. Brown, "Reliability and Fatigue Testing of MEMS," *Tribology Issues and Opportunities in MEMS, NSF/AFOSR/ASME Workshop*, p. 80, Columbus, OH, November 1997.

Nasby, R. D., J. J. Sniegowski, J. H. Smith, S. Montague, C. C. Barron, W. P. Eaton, P. J. McWhorter, D. L. Hetherington, C. A. Apblett, and J. G. Fleming, "Application of Chemical-Mechanical Polishing to Planarization of Surface Micromachined Devices," *Technical Digest of the 1996 Solid State Sensor and Actuator Workshop*, pp. 48–53, Hilton Head Island, SC, 1996.

Nathanson, H. C., W. E. Newell, R. A. Wickstrom, and J. R. Davis, Jr., "The Resonant Gate Transistor," *IEEE Trans. Electron Devices*, Vol. 14, No. 3, pp. 117–133, March 1967.

Nese, M., and A. Hanneborg, "Anodic Bonding of Silicon to Silicon Wafers Coated with Aluminum, Silicon Oxide, Polysilicon or Silicon Nitride," *Sens. Actuators A*, Vol. 37–38, pp. 61–67, 1993.

Nguyen, T. C., "Electromechanical Characterization of Microresonators for Circuit Applications," *Final Report Masters Project*, UC Berkeley, 1991.

Nichols, M. F., "The Challenges for Hermetic Encapsulation of Implanted Devices—A Review," *Crit. Rev. Biomed. Eng.*, Vol. 22, pp. 39–67, 1994.

Nissen, N. F., H. Griese, A. Middendorf, J. Miller, H. Potter, and H. Reichl, "Environmental Screening of Packaging and Interconnection Technologies," *Proceedings of the EcoDesign'99*, pp. 754–759, Tokyo, Japan, 1999.

Noble, M., "Environmental Concerns for Integrated Circuit Sensors," *Meas. Control*, Vol. 19, pp. 210–213, February 1986.

Oh, K. W., and C. H. Ahn, "Development of an Innovative Flip-Chip Bonding Technique Using Micromachined Conductive Polymer Bumps," *Proceedings of the Solid-State Sens. Actuator Workshop*, pp. 170–173, Hilton Head Island, SC, 1998.

Oldfield, S., "Pressure or Depth?," *IEEE OCEANS*, Vol. 94, No. 2, pp. 372–376, 1994.

Olson, R., "Measuring the Stress Component of Conformal Coatings on Surface Mount Devices," *International Symposium on Microelectronics*, pp. 236–247, Boston, MA, 1986.

O'Neal, C. B., A. P. Malshe, S. B. Singh, W. D. Brown, and W. P. Eaton, "Challenges in the Packaging of MEMS," *Proceedings of the International Symposium on Advanced Packaging Materials: Processes, Properties and Interfaces*, pp. 41–47, Braselton, GA, 1999.

Oppermann, H. H., E. Zabel, G. Engelmann, and H. Reichl, "Investigation of Self-Alignment During the Flip-Chip Assembly Using Eutectic Gold-Tin Metallurgy," *Proceedings of the MST'94*, pp. 509–519, Berlin, Germany, 1994.

Oude Nijhuis, M. H. H., T. G. H. Basten, Y. H. Wijnant, H. Tijdeman, and H. A. C. Tilmans, "Transient Nonlinear Response of 'Pull-In MEMS Devices' Including Squeeze Film Effects," *Proceedings of the EUROSENSORS XIII*, pp. 729–732, Hague, The Netherlands, 1999.

Parameswaran, L., V. M. McNeil, M. A. Huff, and M. A. Schmidt, "Sealed-Cavity Microstructure Using Wafer Bonding Technology," *Proceedings of the 7th International Solid-State Sens. Actuators Conference*, pp. 274–277, Yokohama, Japan, 1993.

Park, J. S., and Y. B. Gianchandani, "A Low Cost Batch-Sealed Capacitive Pressure Sensor," *Proceedings of the IEEE MEMS'99*, pp. 82–87, Orlando, FL, 1999.

Patel, S., D. Delaney, D. Xu, G. Murphy, H. Denton, and H. Hughes, "Characterization of Glass on Electronics in MEMS," *Proceedings of SPIE (The International Society for Optical Engineering), Micromachined Devices*, Vol. 3875, pp. 73–79, Santa Clara, CA, September 1999.

Patrick, W., W. Guthrie, C. Standley, and P. Schiable, "Application of Chemical Mechanical Polishing to the Fabrication of VLSI Circuit Interconnections," *J. Electrochemical Soc.*, Vol. 138, No. 6, pp. 1778–1784, 1991.

Peterson, K. E., "Silicon as a Mechanical Material," *Proceedings of the IEEE*, Vol. 70, No. 5, pp. 420–457, 1982.

Petrovic, S., A. Ramirez, T. Maudie, D. Stanerson, J. Wertz, G. Bitko, J. Matkin, and D. J. Monk, "Reliability Test Methods for Media-Compatible Pressure Sensors," *IEEE Trans. Indus. Electron.*, Vol. 45, No. 6, 1998.

Polak, A. J., D. J. Schifferle, and T. Wang, "Semiconductor Device Encapsulation Method," U.S. Patent No. 5,357,673, October 1994.

Putty, M., and K. Najafi, "A Micromachined Gyroscope," *1994 Solid-State Sensors and Actuators Workshop*, pp. 212–220, 1994.

Quenzer, H. J., W. Benecke, and C. Dell, "Low Temperature Wafer Bonding for Micromechanical Applications," *Proceedings of the IEEE MEMS'92*, pp. 49–55, Travemünde, Germany, 1992.

Ramesham, R., and R. Ghaffarian, "Challenges in Interconnection and Packaging of Microelectromechanical Systems," *Proceedings of the 50th Electronic Components & Technology Conference*, pp. 666–675, Las Vegas, NV, May 2000.

Reichl, H., and V. Grosser, "Overview and Development Trends in the Field of MEMS Packaging," *Proceedings of the 14th IEEE International Conference on MicroElectro-Mechanical Systems*, pp. 1–5, Interlaken, Switzerland, 2001.

Ristic, L., F. A. Shemansky, M. L. Kniffin, and H. Hughes, "Surface Micromachining Technology," *Sensor Technology and Devices*, in: L. Ristic, ed., pp. 95–155, Artech House, Boston, MA, 1994.

Robertson, S. V., L. P. B. Katehi, and G. M. Rebeiz, "A 10–50 GHz Micromachined Directional Coupler," *IEEE MTT-S Dig.*, Vol. 2, pp. 797–800, June 1996.

Rodgers, M. S., and J. J. Sniegowski, "5-Level Polysilicon Surface Micromachine Technology: Application to Complex Mechanical System," *Technical Digest of the 1998 Solid State Sensor and Actuator Workshop*, Hilton Head Island, SC, June 1998.

Rodgers, M. S., J. J. Sniegowski, S. L. Miller, C. C. Barron, and P. J. McWhorter, "Advanced Micromechanisms in a Multi-Level Polysilicon Technology," *SPIE Micromachining and Microfabrication Process Technology*, Vol. 3224, pp. 120–130, Austin, TX, September 1997.

Rogers, M. S., et al., "Designing and Operating Electrostatically Driven Microengines," *Proceedings of the 44th International Instrumentation Symposium*, pp. 56–65, Reno, NV, May 1998.

Rogge, B., D. Moser, H. Oppermann, O. Paul, and H. Baltes, "Solderbonded Micromachined Capacitive Pressure Sensors," *Proceedings of the SPIE Micromachined Devices Comp. IV Conference*, Vol. 3514, pp. 307–315, Santa Clara, CA, September 1998.

Romig, A. D., and J. H. Smith, "The Coming Revolution in IC's: Intelligent, Integrated Microsytems," *Proceedings at the 1997 Fall Seminar of Association of Vacuum Equipment Manufacturers*, San Jose, CA, 1997.

Rosenberger, M. E. "Piezoresistive Pressure Transducer with Elastomeric Seals," U.S. Patent No. 4,656,454, April 1987.

Ryan, K., J. Bryzek, and R. Grace, "Flexible Miniature Packaging from Lucas NovaSensor Provides Low-Cost Pressure Sensor Solutions to a Wide Variety of Hostile Media Applications," *ECN*, pp. 118–120, 1995.

Sadiku, M., "MEMS," *IEEE Potentials*, Vol. 21, No. 1, pp. 4–5, 2002.

Sarvar, F., D. A. Hutt, and D. C. Whalley, "Application of Adhesives in MEMS and MOEMS Assembly," *Proceedings of the 2nd IEEE International Conference*, Zalaegerszeg, Hungary, June 2002.

Shaw, K. A., Z. L. Zhang, and N. C. MacDonald, "A Single Mask, Single-Crystal Silicon, Reactive Ion Etching Process for Microelectromechanical Structures," *Sens. Acutators*, Vol. 40, pp. 63–70, 1994.

Shoji, S., B. H. VanderSchoot, N. F. deRooij, and M. Esashi, "A Study of a High-Pressure Micropump for Integrated Chemical Analyzing Systems," *Sens. Actuators*, Vol. A32, pp. 335–339, 1992.

Singh, A., D. A. Horsley, M. B. Cohn, A. P. Pisano, and R. T. Howe, "Batch Transfer of Microstructures Using Flip-Chip Solder Bump Bonding," *International Conference on Solid State Sensors and Actuators (Transducers'97)*, pp. 265–268, 1997.

Sirirak, T. N. P., S. W. Lee, H. Nassef, J. Grasmeyer, Y. C. Tai, C. M. Ho, and M. Keennon, "MEMS Wing Technology for a Battery-Powered Ornithopter," *Proceedings of the 13th IEEE Annual International Conference on MEMS 2000*, pp. 799–804, Miyazaki, Japan, 2000.

Sirirak, T. N. P., Y. C. Tai, H. Nassef, and C. M. Ho, "Unsteady-State Aerodynamic Performance of MEMS Wings," *International Symposium on Smart Structures and Microsystems 2000 (ISHM)*, pp. G1-2, Hong Kong, October 2000.

Sirirak, T. N. P., Y. C. Tai, H. Nassef, and C. M. Ho, "Flexible Parylene Actuator for Micro Adaptive Flow Control," *Proceedings of the 14th IEEE Annual International Conference on MEMS 2001*, pp. 511–514, Interlaken, Switzerland, January 2001.

Smith, B. K., J. J. Sniegowski, G. LaVigne, and C. Brown, "Thin Teflon-Like Films for Eliminating Adhesion in Released Polysilicon Microstructures," *Sens. Actuators A (Physical)*, Vol. A70, pp. 159–163, 1998.

Smith, B. K., J. J. Sniegowski, and G. LaVigne, "Thin Teflon-Like Films for Eliminating Adhesion in Released Polysilicon Microstructures," *International Conference on Solid-State Sensors and Actuators*, Vol. 1, pp. 245–248, Chicago, IL, June 1997.

Smith, J., "Micromachined Sensor and Actuator Research at Sandia's Microelectronics Development Laboratory," *Proceedings of the Sensors Expo*, pp. 119–123, Anaheim, CA, April, 1996.

Smith, J., S. Montague, and J. Sniegowski, "Material and Processing Issues for the Monolithic Integration of Microelectronics with Surface-Micromachined Polysilicon Sensors and Actuators," *SPIE*, Vol. 2639, pp. 64–73, 1995.

Smith, J., S. Montague, J. Sniegowski, J. Murray, and P. McWhorter, "Embedded Micromechanical Devices for the Monolithic Integration of MEMS with CMOS," *Proceedings of the IEDM'95*, pp. 609–612, Washington, DC, 1995.

Smith, J., S. Montague, J. Sniegowski, R. Manginell, P. McWhorter, and R. Huber, "Characterization of the Embedded Micromechanical Device Approach to the Monolithic Integration of MEMS with CMOS," *SPIE*, Vol. 2879, pp. 306–314, October 1996.

Smith, L. and B. Hok, "A Silicon Self-Aligned Nonreverse Valve," *Digest of Technical Papers, International Conference on Solid-State Sensors and Actuators (Transducers 91)*, pp. 1049–1051, San Francisco, CA, June 1991.

Smith, S. S., "Piezoresistive Effect in Germanium and Silicon," *Phys. Rev.*, Vol. 94, No. 1, pp. 42–49, 1954.

Sniegowski, J., and E. Garcia, "Surface-Micromachined Geartrains Driven by an On-Chip Electrostatic Microengine," *IEEE Electron Device Lett.*, Vol. 17, No. 7, p. 366, 1996.

Sniegowski, J., S. Miller, G. LaVigne, M. Rodgers, and P. McWhorter, "Monolithic Geared-Mechanisms Driven by a Polysilicon Surface-Micromachined On-Chip Electrostatic Microengine," *Proceedings of the Solid-State Sensor and Actuator Workshop*, pp. 178–182, Hilton Head Island, SC, 1996.

Sniegowski, J., "Multi-Level Polysilicon Surface Micromachining Technology: Applications and Issues," *ASME International Mechanical Engineering Congress and Exposition*, Atlanta, GA, 1996.

Sniegowski, J., and E. Garcia, "Microfabricated Actuators and their Application to Optics," *SPIE*, Vol. 2383, pp. 46–64, 1995.

Sniegowski, J. J., "Multi-Layer Enhancement to Polysilicon Surface-Micromachining Technology," *IEDM 97 International Electron Devices Meeting*, pp. 903–906, Washington, DC, December 1997.

Sniegowski, J. J., "Chemical Mechanical Polishing: Enhancing the Manufacturability of MEMS," *SPIE Micromachining and Microfabrication Process Technology*, Vol. 2879, pp. 104–115, Austin, TX, October 1996.

Sniegowski, J. J., H. Guckle, and R. T. Christenson, "Performance Characteristics of Second Generation Polysilicon Resonating Beam Force Transducers," *IEEE Solid-State Sensor and Actuator Workshop*, pp. 9–12, Hilton Head Island, SC, 1990.

Soyuer, M., K. A. Jenkins, J. N. Burghartz, and M. D. Hulvey, "A 3-V 4-GHz nMOS VCO With Integrated Resonator," *IEEE International Solid-State Circuits Conference Dig.*, pp. 394–395, San Francisco, CA, 1996.

Sparks, D. R., L. Jordan, and J. H. Frazee, "Flexible Vacuum-Packaging Method for Resonating Micromachines," *Sens. Actuators*, Vol. 55, pp. 179–183, 1996.

Spooner, et al., "Method and Device for Protecting Micro Electromechanical System Structures during Dicing of a Wafer," U.S. Patent No. 6,555,417, 2003.

Suhir, E., "Modeling of the Mechanical Behavior of Materials in 'High-Tech' Systems: Attributes and Review," *ASME J. Electron. Packag.*, Vol. 121, No. 4, pp. 213–221, 1996.

Sze, S. M., (ed), *Semiconductor Sensors*, Wiley Interscience, New York, 1994.

Tabata, O., K. Kanahata, S. Sugiyama, and I. Igarashi, "Mechanical Property Measurements of Thin Films Using Load-Deflection of Composite Rectangular Membranes," *Sens. Actuators*, Vol. 20, pp. 135–141, 1989.

Tummala, R. R., E. J. Rymaszewski, and A. G. Klopfenstein, *Microelectronics Packaging Handbook*, Van Nostrand, New York, 1989.

Tang, W., T. C. Nguyen, and R. Howe, "Laterally Driven Polysilicon Resonant Microstructures," *Sens. Actuators*, Vol. 20, pp. 25–32, 1989.

Tanner, D. M., W. M. Miller, W. P. Eaton, L.W. Irwin, K. A. Peterson, M. T. Dugger, D. C. Senft, N. F. Smith, P. Tangyunyong, and S. L. Miller, "The Effect of Frequency on the Lifetime of a Surface Micromachined Microengine Driving a Load," *IEEE International Reliability Physics Symposium Proceedings*, pp. 26–35, Reno, NV, March 1998.

Tanner, D. M., N. F. Smith, D. J. Bowman, W. P. Eaton, and K. A. Peterson, "First Reliability Test of a Surface Micromachined Microengine Using SHiMMeR," *Proceedings of 1997 Symposium on Micromachining and Microfabrication*, Vol. 3224, pp. 14–23, Austin, TX., September 1997.

Tanner, D. M., J. A. Walraven, L. W. Irwin, M. T. Dugger, N. F. Smith, W. M. Miller, and S. L. Miller, "The Effect of Humidity on the Reliability of a Surface Micromachined Microengine," *Proceedings of IEEE International Reliability Physics Symposium*, pp. 189–197, Hilton Head Island, SC, 1999.

Tilmans, H., et al., "The Indent Reflow Sealing (IRS) Technique—a Method for Fabrication of Sealed Cavities for MEMS Devices," *JMEMS*, Vol. 2, No. 2, pp. 206–217, June 2000.

Tilmans, H. A. C., E. Fullin, H. Ziad, M. D. J. VandePeer, J. Kesters, E. VanGeffen, J. Bergqvist, M. Pantus, E. Beyne, K. Baert, and F. Naso, "A Fully Packaged Electromagnetic Microrelay," *Proceedings of the IEEE MEMS'99*, pp. 25–30, Orlando, FL, 1999.

Tirén, J., L. Tenerz, and B. Hok, "A Batch-Fabricated Non-Reverse Valve with Cantilever Beam Manufactured by Micromachining of Silicon," *Sens. Actuators*, Vol. 18, pp. 389–396, 1989.

Tomase, J. P., S. H. Chen, G. D. Stamm, and M. K. Chason, "Hermetically Sealed Interface," U.S. Patent No. 5,173,836, December 1992.

Tufts, O. N., and E. L. Stelzer, "Piezoresistive Properties of Silicon Diffused Layers," *J. Appl. Phys.*, Vol. 34, No. 2, pp. 313–318, 1963.

VanLintel, H. T. G., F. C. M. VandePol, and A. Bouwstra, "Piezoelectric Micropump Based on Micromachining of Silicon," *Sens. Actuators*, Vol. 15, No. 2, pp. 153–168, 1988.

VanVeen, C., "Analytical Derivation of the Self-Alignment Motion of Flip Chip Soldered Components," *Trans. ASME J. Electron. Packag.*, Vol. 121, pp. 116–121, 1999.

Veijola, T., H. Kuisma, and J. Lahdenperä, "The Influence of Gas–Surface Interaction of Gas-Film Damping in a Silicon Accelerometer," *Sens. Actuators*, Vol. 66, pp. 83–92, 1998.

Viswanadham, P., and P. Singh, *Failure Modes and Mechanisms in Electronic Packages*, Chapman & Hall, New York, 1997.

Vujosevic, M., and M. Shah, " Isolation of a Die in a Post-molded Plastic Package from Time Dependent Deformation Mechanisms: The Role of Die Coat," submitted for publication.

Vujosevic, M., "The Impact of Die Attach Thickness and the Dome Coat Coverage on Strains in the Inter-Chip Wire Bonds in the Medium g Accelerometer Packages," *Simulation & Modeling for 10x Cycle Time Reduction Symposium*, Motorola, Phoenix, AZ, 1996.

Wang, et al., "Low Defect Method for Die Singulation and for Structural Support for Handling Thin Film Devices," U.S. Patent No. 6,573,156B1, 2003.

Wang, X. Q., Q. Lin, and Y. C. Tai, "A Parylene Micro Check Valve," *12th IEEE International Conference on Micro Electro Mechanical Systems*, pp. 177–182, FL, January 1999.

Wang, X. Q., X. Yang, K. Walsh, and Y. C. Tai, "Gas-Phase Silicon Etching with Bromine Trifluoride," *Digest of Technical Papers, 9th International Conference on Solid-State Sensors and Actuators (Transducers'97)*, Vol. 2, pp. 1505–1508, Chicago, IL, June 1997.

Weinberg, H., “Building a Tiny Accelerometer to Detect Very Small Signals,” *Sensors*, Vol. 18, No. 2, February 2001.

Wolffenbuttel, R. F., “Low-Temperature Intermediate Au-Si Wafer Bonding; Eutectic or Silicide Bond,” *Sensor Actuat. A-Phys.*, Vol. 62, No. 1–3, pp. 680–686, 1997.

Wood, R.A., et al., “Method for Making a Wafer-Pair having Sealed Chamber,” U.S. Patent No. 6,036,872, March 2000.

Yao J. J., and M. F. Chang, “A Surface Micromachined Miniature Switch for Telecommunications with Signal Frequencies from dc to 4 GHz,” *8th International Conference on Solid-State Sensors and Actuators*, pp. 384–387, Stockholm, Sweden, June 1995.

Yao, T. J., X. Yang, and Y. C. Tai, “BrF3 Dry Release Technology for Large Freestanding Parylene MEMS,” *Digest of Technical Papers*, *11th International Conference on Solid-State Sensors and Actuators (Transducers’01)*, pp. 652–655, Munich, Germany, June 2001.

York, R. A., and Z. B. Popovic, *Active and Quasi-Optical Arrays for Solid-State Power Combining*, Wiley, New York, 1997.

Young, D. J. and B. Boser, “A Micromachined Variable Capacitor for Monolithic Low-Noise VCO’s,” *Solid-State Sensors and Actuator Workshop Technical Digest*, pp. 86–89, Hilton Head Island, SC, 1996.

Yun, W., R. Howe, and P. Gray, “Surface Micromachined, Digitally Force-Balanced Accelerometer with Integrated CMOS Detection Circuitry,” *Proceedings of the Solid-State Sensor and Actuator Workshop*, p. 126, San-Sebastian, Spain, October, 1992.

Zavracky, P., G. Adams, and P. Aquilino, “Strain Analysis of Silicon-on-Insulator Films Produced by Zone Melt Recrystallization,” *J. Microelectromech. S.*, Vol. 4, No. 1, pp. 42–48, 1995.

Zhang, Z. L., and N. C. MacDonald, “Fabrication of Submicron High-Aspect-Ratio GaAs Actuators,” *J. Microelectromech. S.*, Vol. 2, pp. 66–72, 1993.

Ziaie, B., J. VonArx, M. Dokmeci, and K. Najafi, “A Hermetic Glass-Silicon Micropackage with High Density On-Chip Feedthroughs for Sensors and Actuators,” *IEEE JEEMS*, Vol. 5, No. 3, pp. 166–179, September 1996.

Ziaie, B., J. VonArx, M. Nardin, and K. Najafi, “A Hermetic Packaging Technology with Multiple Feedthroughs for Integrated Sensors and Actuators” *Proceedings of the 7th International Solid-State Sensors and Actuators Conference*, pp. 266–269, Yokohama, Japan, 1993.

This page intentionally left blank

Index

0-level, 25, 26
Accelerometer, 15, 25, 26, 31, 34–37, 47, 50, 51, 53, 57, 70, 75, 83, 90, 122, 124, 129, 133, 148, 149, 152, 189
Actuation (*see* Actuator)
Actuator, 39–43, 45, 58, 59, 76, 111
  bimorphic, 40, 42, 43
  electrostatic, 40–42, 58
  electromagnetic, 40, 42
  piezoelectric, 40, 43, 45
  resonator, 32, 36, 53
ADXRS, 47, 48
AIBO, 52
Air bag, 34, 35, 47, 50, 51, 83, 152
Air bag sensor (*see* Air bag)
Air cavity, 24
Antistiction, 148–150, 175, 178–179, 181
Antistiction agent (*see* Antistiction)
Applications, 50–58, 59–63, 84, 86, 89, 90, 97, 101, 107, 111, 116, 152, 153, 155, 164, 168, 176, 177, 193, 197, 200
Assembly, 2–5, 11–15, 17–18, 19, 21, 23, 28, 31, 46, 63, 66, 70–72, 76, 85, 86, 88, 90, 91, 97, 102, 111, 116
Automotive sensor, 10

Ball Grid Array (BGA), 4, 5, 13, 90, 134
Barrier, 10, 21, 25, 27, 75, 80, 83, 95, 99, 100, 105, 106, 114, 140, 144, 155, 156, 169, 170, 174, 194, 197
Barrier coating, 10, 27, 84, 106, 154, 161, 162
BGA (*see* Ball Grid Array)
Bonding pad, 11, 15, 25, 92, 131
Boron (B), 45, 46, 132, 133, 160
Bromine (Br), 6, 99, 160, 167, 168
Bump(s)/bumping, 5, 11, 13, 14, 17, 93, 124, 131, 133, 134, 137, 138, 172, 199
Burn-in, 18, 102

CAD, 16, 19, 44
Capacitance, 10, 35, 37, 40, 47, 53, 150
Capped device (*see* Capping)
Capping, 25, 26, 66, 71, 83, 90, 91–93, 108, 122, 123, 126, 128–132, 154, 155, 164
Cap (*see* Capping)
Carbon Nanotube (CNT), 161, 186, 189, 193, 198
Catalyst, 8, 107, 166, 194
Cathode Ray Tube (CRT), 7, 30, 163
Chemical, 5, 8, 15, 17, 21, 35, 36, 38, 43, 46, 48, 53, 55, 57, 68, 73, 75, 78, 79, 83, 122, 123, 138, 148, 149, 160–166, 170, 176–179, 186, 187, 189–192
Chemical detectors (*see* Sensor, chemical)
Chemical reaction (*see* Chemical)
Chemical reactor (*see* Chemical)
Chemical reagents (*see* Chemical)
Chip, 1, 4, 7, 11, 15–19, 21–23, 25, 26, 30, 31, 33, 34, 38, 39, 47, 49, 52, 55, 56, 59, 60, 61, 63, 65, 66, 70–74, 76–79, 88, 91–94, 96, 97, 101–103, 111, 112, 116, 117, 121, 122, 129–138, 143, 148, 151, 153–156, 162, 172, 184
  bonding, 4, 12, 23–25, 94
  carrier, 4, 22, 24, 88, 111
  flip, 4, 8, 10, 11, 18, 69, 124, 133, 135, 162, 172
Chip scale (*see* Chip Scale Package)
Chip Scale Package (CSP), 1, 4, 13, 84, 131, 138, 139
Chip-on-Board (COB) (*see* Chip, flip)
Chipscale (*see* Chip Scale Package)

Copyright © 2005 by The McGraw-Hill Companies, Inc. Click here for terms of use.

CNT (*see* Carbon Nanotube)
COB (Chip-on-Board) (*see* Chip, flip)
Coefficient of hygroscopic expansion, 107
Coefficient of static friction, 181
Coefficient of thermal expansion (CTE), 16, 68, 71, 132, 167, 199
Compatibility, 2, 11, 13, 14, 84, 111, 140
Conductive adhesive, 11, 14, 72, 133, 134, 172
Conductor, 12, 15, 45, 63, 80, 84, 97, 103, 129, 160–162, 186
Conformal coating, 149
Connection, 2, 4, 8, 11–13, 15, 18, 19, 23, 25, 26, 66, 78, 92, 100, 101, 108, 116, 131, 133, 135, 136, 138, 139, 172
Connectivity, 8, 9, 112, 195
Contamination, 10, 25, 69, 70, 75, 91, 94, 104, 112, 123, 126–128, 134, 139, 151, 153, 172, 173, 181
Corrode (*see* Corrosion)
Corrosion, 8, 10, 21, 75, 81, 98, 133, 154, 176
Cost, 3–6, 9, 10, 11, 16, 18–24, 26–28, 33, 46, 47, 50–53, 63, 67–69, 74, 79, 80, 82–85, 88–92, 97, 99–102, 106, 107, 111, 113, 116, 121, 122, 138, 140, 145, 154–156, 159, 161, 171, 179, 181, 200
Cross-link, 8, 167
CRT (*see* Cathode Ray Tube)
CSP (*see* Chip Scale Package)
CTE (*see* Coefficient of thermal expansion)

DCA (*see* Chip, flip)
Decompose (*see* Decomposition)
Decomposition, 14
Deep Reactive Ion Etching (DRIE), 18
DeForest, 20
Device, 4, 7, 8, 10, 11, 18, 20, 24–29, 31, 37, 38, 39, 96, 190, 192
(*See also* Chip)
Device:
- nano, 192, 194, 200, 201
- silicon-based, 30
- electromechanical, 33, 35, 37, 43, 47, 49, 52–55, 57, 65, 66, 69, 71, 72, 75, 79, 86, 90–92, 94, 97, 108, 121–125, 128, 131–134, 140, 145, 149, 151–155, 171, 174–176, 188, 189
- materials, 44, 83
- opto-electromechanical, 58, 65, 70, 112–16, 135, 142, 143, 153, 155, 172, 178, 184

Diaphragm, 10, 37
Die attach adhesive, 17, 23, 25, 71, 73, 75, 122, 135, 141
Die shrink, 11
Die stacking, 15
Digital projector, 30, 60, 63, 112
DIP (*see* Dual In-line Package)
Direct Chip Attach (DCA) (*see* Chip, flip)
DLP mirror chip, 22, 24, 26, 30, 46, 58–61, 63, 64, 70, 83, 110, 112, 113, 116, 128, 142, 149, 164, 171, 173, 175, 177, 184
(*See also* Digital projector)
DNA, 24, 29, 164, 189, 193, 193
DRIE (*see* Deep Reactive Ion Etching)
Dual In-line Package (DIP), 3, 4, 88

Economics (*see* Cost)
Elastomeric gel, 10, 66
Electrical interconnect 2, 19, 27, 69, 84, 101, 160, 195, 200
(*See also* Connection)
Encapsulation, 3, 19, 66, 92, 93, 94, 138, 139, 154
Energy, 9, 17, 31, 33, 37, 39, 43, 52, 53–55, 75, 79, 97, 104–06, 114, 123, 130, 137, 142–145, 146–149, 166, 167, 174, 178, 179, 181, 192, 197
Energy extractor, 39, 52, 53
Environmental protection, 2
(*See also* Encapsulation)
Epoxies (*see* Epoxy)
Epoxy, 5, 6, 14, 23–25, 28, 47, 71, 72, 83, 91, 92, 99, 112, 114, 122, 140, 141, 142, 166, 167, 168, 173
Epoxy resin (*see* Epoxy)
Etching, 45, 46, 68, 123–125, 128, 129, 132, 133, 138, 162, 178, 195
Eyelet, 87

Fan-in, 15, 138
Fan-out, 12, 15, 138
FC (*see* Chip, flip)
FCIP (*see* Chip, flip)
FCOB (*see* Chip, flip)
Flame retardant, 6, 99
Flammability, 6, 96, 99, 160, 167, 169
Fleming, 20
Flexible circuitry, 3, 11, 16, 84, 90, 97, 116, 136, 161, 170
Flip Chip (FC) (*see* Chip, flip)
Flip-Chip-in-Package (FCIP) (*see* Chip, flip)

Fluid, 8, 10, 15, 31, 38, 51, 52, 59, 66, 69, 70, 73, 74, 76, 78, 80, 90, 97, 114, 116, 125, 128, 136, 140, 148, 149, 171, 193
Fluidic, 19, 53, 100, 192
Fluid pump, 9, 56, 77
Fluidic MEMS, 77, 78, 117, 118, 190
(*See also* Fluid; Fluidic; Fluid pump)
Foundry, 33, 66, 92, 123, 124, 129
FR (*see* Flame retardant)
FR4, 5, 165
Free-space, 8, 66, 172
Friction, 76, 145, 149, 152, 179, 180, 181

GaAs, 22
Gas analyzer, 9, 74
Gas-tight, 114, 118
Gear(s), 33, 70, 125, 183, 184
Gel, 10, 66, 91, 97, 133, 154
Germanium (Ge), 45, 46
Getter(s), 22, 59, 73, 74, 115, 118, 151–153, 175–178, 181
Gigahertz, 8
Glass, 1, 6, 7, 9, 10, 20, 21, 22, 24, 27, 49, 59, 66–68, 71, 78, 83, 86–88, 91–93, 100, 102, 104, 106, 108, 112–114, 116, 129, 130, 140–144, 146, 155, 160, 163, 164, 168, 169, 174, 183, 191, 197, 198
Glass Transition Temperature (Tg), 6
Gold (Au), 11, 12, 22, 27, 41, 45, 67, 71, 77, 87, 97, 100, 101, 103, 116, 133, 134, 137, 146, 159, 160–165, 172, 174
Gull wing, 3
Gyroscope, 25, 34, 35, 47, 48, 50, 51, 57, 97, 102, 112, 122, 129, 132

Halogen, 6, 96, 99, 167
Hardener, 23, 24, 140, 141, 166, 167
Heat management, 2
Helium fine leak test, 22, 80–82, 104, 105, 107, 114, 143
Hermetic, 3, 6–9, 14, 17, 19–28, 30, 31, 49, 57, 59, 66, 67–69, 73–75, 79–86, 88–93, 100, 105–107, 112–116, 118, 121, 130–133, 140, 142, 143, 146, 151–156, 159, 163, 164, 168, 170, 171, 174–176, 181, 201
Hermetic package (*see* Package, hermetic)
Hermeticity, 8, 9, 19, 24, 26–28, 68, 69, 79, 80–84, 89, 91, 105, 106, 112–114, 118, 131, 143, 153–156, 159, 171, 181
Hydrogen (H), 22, 73, 76, 99, 105, 151, 160, 164, 175, 177
Hydrophobic, 10, 66, 69, 75, 76, 106, 148, 149, 154, 178, 181

ILB (*see* Inner Lead Bonding)
Inertial Sensor (*see* Sensor, inertial)
Injection molding, 24, 68, 85, 89–91, 96–98, 100, 106, 107, 111, 122, 167, 170, 181
Ink jet, 8, 12, 13, 19, 31, 32, 43, 52, 53, 55, 69, 74, 79, 116, 117, 121, 138, 139, 153
Inner Lead Bonding (ILB), 11, 136, 137, 138
Input/output (I/O), 4, 8, 9, 14, 18, 21, 24, 47, 50, 67, 79, 80, 83, 84, 86, 101, 154
Insert molding, 33, 34, 37
I/O (*see* Input/output)

KGD (*see* Known Good Die)
Known Good Die, 18

Land Grid Array, 4
Laser, 9, 45, 67, 68, 69, 86, 102, 104, 105, 112–114, 116, 118, 122, 128, 133, 135, 138, 141–144, 146, 150, 148, 172, 174, 175, 192, 196, 197
Laser sealing (*see* Laser welding)
Laser welding, 102, 104, 143
(*See also* Laser)
LCP (*see* Liquid Crystal Polymer)
Lead-free, 2, 6, 14, 96, 101, 107, 167, 169, 171, 172
LED (*see* Light Emitting Diode)
LGA (*see* Land Grid Array)
Lid, 24, 59, 68, 77, 80, 83, 86, 88, 98, 102, 103–105, 108, 110, 114, 122, 139, 140–143, 145, 146–148, 151, 152, 155, 174, 176
Lid sealing, 38–40, 44, 122, 139, 141, 142, 174
(*See also* Laser welding)
LIGA (Lithographie, Galvanformung, Abformung), 46
Light Emitting Diode (LED), 4, 9, 148, 165, 196
Liquid Crystal Polymer (LCP), 12, 80, 83, 96, 97, 99, 100, 101, 104, 106, 107–12, 114, 136, 169–171, 174
Lithographie, Galvanformung, Abformung (*see* LIGA)

Manufacturing, 5, 21, 35, 45–46, 49, 63, 82, 84–86, 90, 97, 100, 112, 116, 117, 128, 156, 193, 198
Materials, 5, 6, 9–11, 16, 18, 19, 21–23, 32, 35, 36, 38, 42–44, 45, 46, 52, 57, 60, 66, 68, 71, 74–76, 83–84, 85–90, 93–95, 99–101, 105–106, 113, 116–117, 133–136, 139, 140, 142–146, 148–151, 154, 155, 159–182, 188, 189, 200
  permanent (*see* structural *below*)
  sacrificial, 45, 46, 123, 124, 128
  structural, 40, 42, 44–46, 122–124, 126
Membrane, 10, 39, 74, 118, 193
MEMS-specific package, 26, 50, 111, 200
Metal finish, 14, 162
Metal Lead Frame (MLF), 4, 23, 84, 95, 97–100, 112
Metal pad, 2, 3, 4, 17, 196
Micro-Structured Technology (MST), 32, 33
Military MEMS, 23, 26, 50, 57, 85, 175, 176
MIL-STD-883, 80, 81, 114, 177
MLF (*see* Metal Lead Frame)
Mirror, 23, 30, 31, 39, 41, 49, 58, 61, 63, 64, 70, 112, 128, 153, 172, 176, 177, 178, 184, 185, 197
Modulus, 10, 16, 17, 66, 72, 108, 170, 173
Moore's Law, 1
MST (*see* Micro-Structured Technology)
Multichip, 1, 84, 90, 148

Nano-Electro-Mechanical System (NEMS), 23, 184, 186, 192, 198, 201
Nanotechnology, 1, 33, 34, 118, 161, 165, 183–189, 191–201
Nanoelectronics, 193–196, 198, 200, 201
Near Hermetic Package (NHP) (*see* Package, near-hermetic)
NEMS (*see* Nano-Electro-Mechanical System)
NHP (*see* Package, near-hermetic)

OLB (*see* Outer Lead Bonding)
OLED (*see* Light Emitting Diode)
Optical-MEMS, 29, 49, 58, 83, 112
Optoelectronic, 2, 6, 7, 9, 14, 19, 21, 66, 67, 74, 85, 111–113, 116, 118, 148, 152, 174, 196, 200
Organic Light Emitting Diode (*see* Light Emitting Diode)
Outer Lead Bonding (OLB), 12, 137, 138
Oxidize, 8, 162, 178, 194

Package, 1–28, 38, 39, 44, 47, 50, 52, 55, 57, 59, 64, 65–119, 121, 122, 127, 131, 133–157, 159, 160–162, 164, 168–171, 174–177, 180, 181, 196, 200
  class, 7, 26, 137
  hermetic, 7, 9, 14, 17, 19–24, 26, 31, 67, 68, 74, 79, 80, 85, 86, 89, 90, 133, 151, 152, 164, 175, 176
  near-hermetic, 24, 26–28, 67, 73, 82, 83, 102, 111, 118
  nonhermetic, 21, 23–27, 28, 30, 73, 82, 83, 90, 112, 114
  premolded, 96–108, 154, 155, 170
  post-molded, 30, 94–96
  stacked, 1, 5, 15, 84, 147
Pad size, 11
Palladium (Pd), 22, 67, 100, 101, 160–162, 175
Parts library, 19, 44
Passivation, 7, 11, 74, 128, 154–156, 178
PBGA (*see* Plastic Ball Grid Array)
PCB (*see* Printed circuit board)
PEM (*see* Plastic Encapsulated Microelectronics)
Performance enhancement, 2, 18
Perimeter, 4, 14, 24, 111, 134, 135, 146
Perimeter paralysis, 4
PGA (*see* Pin Grid Array)
Phosphorus (P), 6, 96, 99, 160, 167
Photodetector, 9, 49, 148
PI (*see* Polyimide)
Piezo, 10, 36, 37, 43, 45, 52, 145
Piezoresistive, 10, 36
Pin count, 9
Pin Grid Array (PGA), 4, 72, 90, 131
Plastic Ball Grid Array (PBGA), 5
Plastic Encapsulated Microelectronics (PEM), 23, 90, 94
Plastic package, 3, 5, 19, 21, 23, 24, 27, 28, 50, 80, 82–84, 90–91, 94, 103, 106, 112, 143, 144, 155, 160, 171
Platform, 4, 22, 24, 50, 74, 86, 99, 135, 139, 161, 162, 164, 200
Platinum (Pt), 22, 160
Pluggable, 16, 18, 62, 72, 73, 131

Polyimide (PI), 11, 45, 107, 108, 136, 138
Polymer (*see* Liquid Crystal Polymer; Polyimide; Thermoplastics; Thermoset)
Polymerization, 6, 25, 72, 140–142, 149, 150, 165, 166, 170
Popcorning, 8, 31
Port, 54, 70, 74, 118, 135
Pressure sensor (*see* Sensor, pressure)
Printed circuit board (PCB), 2, 5, 12, 14, 16–18, 63, 93, 122, 131, 137, 138, 168, 170, 199
Printed wiring board (PWB) (*see* Printed circuit board)
Propulsion, 3, 27, 43, 55
PWB (*see* Printed circuit board)

QFN (*see* Quad Fine-pitch No-lead)
Quad Fine-pitch No-lead (QFN), 4, 79, 80, 112, 154
Quasi-hermetic 25, 26

Reactive Ion Etching (RIE), 45, 46, 133
Reliability, 7, 9, 18, 22, 26–28, 35, 44, 45, 53, 57, 89, 113, 129, 131, 151–154, 170, 175, 176, 200
Residual Gas Analysis (RGA), 22
Restriction of Hazardous Substances (RoHS), 6, 14
Reworkability, 18
RF-MEMS, 32, 53, 57, 86
RF shielding (*see* Shielding)
RGA (*see* Residual Gas Analysis)
RIE (*see* Reactive Ion Etching)
RoHS (*see* Restriction of Hazardous Substances)
Routing, 2, 9, 11, 14–16, 65, 69, 101

SAM (*see* Self-assembled monolayer)
Sawing (*see* Singulation)
Sealing (*see* Lid sealing)
Self-assembled monolayer (SAM), 29, 76, 149, 178
Semiconductors, 1, 2, 8, 22, 28, 29, 94, 187, 194
Sensor:
- chemical, 38, 48
- force, 10, 37, 75
- inertial, 18, 31–37, 50–52, 57, 66, 75, 80, 83, 91, 121, 124, 128, 171, 173, 189
- motion (*see* inertial *above*)
- pressure, 10, 32, 34–37, 47, 50–53, 66, 72, 75, 83, 108, 116, 125, 131

Shielding, 77
Silicon Dioxide (SiO_2), 8, 17, 18, 36, 106, 124, 153, 160, 163, 167, 178, 191, 194–196, 199
Silicone, 10, 69, 72, 76, 97, 108, 114, 133, 148, 149, 154, 178
Singulation, 91, 92, 126–129, 172
SiP (*see* System-in-package)
SMD (*see* Surface Mount Device)
SMT (*see* Surface Mount Technology)
Solder joint, 2, 17, 114
Solderable area array, 4
Soldering, 5, 6, 8, 12, 13, 68, 95–97, 101, 106, 107, 113, 114, 137, 140, 142, 143, 146, 160, 162, 167, 169, 171, 199
Solid-state, 7, 8, 21, 25, 29
Spectrophotometer, 16, 52, 59, 62, 63, 148
Standardization, 2, 19, 44, 45, 67
Stiction, 75, 76, 124, 125, 148–150, 152, 175, 176, 178–181
Stress, 11, 16, 17, 23, 25, 36, 37, 43, 47, 57, 58, 66, 68, 71, 72, 81, 91, 92, 97, 115, 122, 133, 149, 150, 164, 167, 173, 189, 190
Stress-reduction, 17
SUMMiT V, 46
Surface Machining, 46, 63
Surface Mount Device (SMD), 4, 5, 23, 102
Surface Mount Technology (SMT), 3 (*See also* Surface Mount Device)
Synthesis, 55, 57, 117
System-in-package 16, 164

TAB (*see* Tape Automated Bonding)
Tape Automated Bonding (TAB), 11–13, 15, 84, 133, 136–139, 171
Tape Ball Grid Array (TBGA), 13, 15, 138
TBGA (*see* Tape Ball Grid Array)
Temperature and humidity, 2, 107, 108, 110
Testability, 2
Tg (*see* Glass Transition Temperature)
T&H (*see* Temperature and humidity)
Thermal, 8, 11, 16–18, 40, 43, 68, 71, 72, 76, 88–90, 96, 108, 114, 132, 135, 138, 145, 149, 155, 163, 164, 167, 168, 170, 171, 178, 193, 199, 200
Thermal compression, 11
Thermal management, 115–116
Thermal pad, 17

Thermoplastics, 5, 6, 12, 14, 25, 72, 96, 99, 100, 106, 107, 114, 141–145, 155, 160, 165, 167–170, 175
Thermoset, 5, 6, 14, 24, 28, 66, 71, 72, 90, 99, 135, 140, 165–168, 170, 174, 181
Thermoset plastic (*see* Thermoset)
Tin-lead (SnPb), 14, 169
Transfer molding 23, 24, 28, 90, 94, 96, 100, 170, 181
Transmission welding, 105
Turbine, 43, 53, 54

Underfill, 11, 16–19, 23, 134–136, 139, 199, 200
UV-curable, 10, 83, 112, 114, 139, 141–142, 144, 173
UV-erasable, 9

Wafer bonding, 45, 66, 91, 93, 126, 132, 133
Wafer Level Package (WLP), 5
Wafer thinning, 17, 117
Wafer-level, 5, 18, 25, 26, 29, 45, 46, 66, 82, 90–93, 116, 123, 124, 126, 132, 133, 136, 148, 149, 156
Wafer-level testing, 18
Water vapor, 8, 43, 80, 107, 108, 176, 177, 178
Water vapor transmission, 107, 108
Wear, 31, 70, 71, 76, 78, 94, 152, 153, 177, 179–181
Window, 10, 12, 21, 59, 112–116, 136, 138, 163
Wire:
  aluminum, 11, 172
  bonding (*see* Wire bonding)
  copper, 11, 161
  gold, 11, 97, 103, 163, 171, 172
Wire bonding, 4, 8, 11–16, 23, 25, 45, 66, 68, 71, 72, 75, 87, 92, 93, 97, 101–122, 131, 133, 144, 148, 162, 163, 171, 172
WLP (*see* Wafer Level Package)

ABOUT THE AUTHOR

Ken Gilleo, Ph.D., is the CEO of ET-Trends, a consulting, packaging design, and IP firm specializing in emerging technologies. The firm's projects include novel materials and packages and processes for MEMS, MOEMS, and optoelectronics. Dr. Gilleo is a member of IEEE, and he is also Vice President of Technical Programs for the Surface Mount Technology Association (SMTA). He has been actively involved in the development of new products for 30 years and is an inventor in circuitry, electronics materials, and packaging. Dr. Gilleo has 30 U.S. patents, and his products have received three R&D 100 Awards. Dr. Gilleo resides in Warwick, Rhode Island.

Copyright © 2005 by The McGraw-Hill Companies, Inc. Click here for terms of use.