Microelectromechanical Systems

Advanced Materials and Fabrication Methods

Committee on Advanced Materials and Fabrication Methods for Microelectromechanical Systems

National Materials Advisory Board

Commission on Engineering and Technical Systems

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Cover: Rotating grating on a 200 μm diameter gear that allows 180 degrees of positioning. The grating is 185 μm x 200 μm with 2 μm wide lines and spaces. The device has the potential to be used as a beam splitter or as a diffractive element in a microspectrometer. The system was designed by Major John Comtois and Professor Victor Bright, U.S. Air Force, and fabricated by the DARPA-sponsored MCNC MUMPs program. Courtesy of J.H. Comtois and V.M. Bright, U.S. Air Force.

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PHILLIP W. BARTH, Hewlett-Packard Laboratories, Palo Alto, California
SELDEN B. CRARY, University of Michigan, Ann Arbor
DENICE D. DENTON, University of Washington, Seattle
KAREN W. MARKUS, MEMS Technology Applications Center at MCNC, Research Triangle Park, North Carolina
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ROBERT E. NEWNHAM, Pennsylvania State University, University Park
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PAT WILLIAMS, Senior Project Assistant
CHARLES HACH, Research Associate
JOHN A. HUGHES, Research Associate
BONNIE A. SCARBOROUGH, Research Associate

Technical Consultants

GEORGE M. DOUGHERTY, U.S. Air Force, Wright Patterson Air Force Base, Ohio
JASON HOCH, MEMS Technology Applications Center at MCNC, Research Triangle Park, North Carolina
HOWARD LAST, Naval Surface Warfare Center, Silver Spring, Maryland
NOEL C. MACDONALD, Defense Advanced Research Projects Agency, Arlington, Virginia

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Preface

Many people in the field of microelectromechanical systems (MEMS) share the belief that a revolution is under way. As MEMS begin to permeate more and more industrial procedures, not only engineering but society as a whole will be strongly affected. MEMS provide a new design technology that could rival, and perhaps even surpass, the societal impact of integrated circuits (ICs). Is this fact or fiction? If it is fact, then several questions must be asked.

- What precisely is the nature of this "revolution"?
- What should be done to exploit MEMS in the most advantageous way?
- Are lessons learned from the development of other fields applicable to the future of MEMS?
- What are the risks of various strategies?
- What steps can be taken to provide an environment in the U.S. that promotes healthy and vigorous growth for MEMS?

A brief consideration of the nature of the revolution can provide a focus for further discussion. Although the revolution may seem to be nothing more than the "miniaturization of engineering systems" to some observers, the authors of this report believe that much more is involved. Miniaturization per se is more of an evolutionary than a revolutionary process. Building systems as compactly as possible has been a theme of engineering practice for many years, and progress toward this goal is typically measured in terms of countless refinements in design and manufacturing techniques.

MEMS is a new and revolutionary field because it takes a technology that has been optimized to accomplish one set of objectives and adapts it for a new, completely different task. The industry, of course, is the silicon-based IC process, which is now so highly refined that it can produce millions of electrical elements on a single chip and define their critical dimensions to tolerances of 100-billionths of a meter. Countless hours and dollars were invested in this technology over the past 30 years to develop a superb method for fabricating overwhelmingly complex electrical systems. The MEMS revolution arises directly from the ability of engineers to harness IC know-how and use it to build working microsystems from micromechanical and microelectronic elements. Because the committee believes that this adaptation is the revolutionary aspect of MEMS, this report will strongly emphasize those "lithography-based" processing methods that have been well established through the IC experience.

MEMS is a multidisciplinary field that involves challenges and opportunities for electrical, mechanical, chemical, and biomedical engineering, as well as for physics, biology, and chemistry. Papers describing developments in MEMS are being presented more and more frequently at research meetings that have traditionally focused on other fields, such as the large and respected annual International Electron Devices Meeting of the Institute of Electrical and Electronics Engineers (IEEE). Articles about these conferences in trade publications indicate the importance of MEMS to ICs in the gigabit era. One finds "evening discussion sessions," for example, that explore the impact of MEMS on the design of control systems, displays, optical systems, fluid systems, instrumentation, medical and biological systems, robotics, navigation, and computers, among other fields. Universities worldwide are incorporating MEMS research into their programs. To accommodate the interdisciplinary features of the field, many universities are creating cross-departmental and cross-college programs. New graduate courses are being introduced using new materials for teaching, and several books on the subject are nearing completion.

A significant number of government programs supporting MEMS development are in place around the world (e.g., Japan, Switzerland, Germany, Taiwan, and Singapore), and the list is growing. This suggests that development will accelerate as new applications and product opportunities become evident. One can see a similarity to the parallel, independent development of ICs that coalesced in the early 1970s, after a decade or so of intense development had led to processes and designs suitable for use in marketable products.

Early federal support for MEMS research in the United States came from the National Science Foundation, which recognized the field as an emerging area of opportunity. This very limited support (less than $1 million per year) was only for prototype demonstrations, however. In recent years, a major additional source of federal funds has been the U.S. Department of Defense, which currently supports a program at a level of more than $50 million per year.

Only now are established industries in the United States becoming aware of the potential effects of MEMS on their products, and a "show me" attitude has arisen in many quarters. Interest has been steadily increasing with the success of a number of MEMS pioneer companies (e.g., Analog Devices, Inc., EGG IC Sensors, and NovaSensor) in developing commercially rewarding products. More than 80 U.S. firms currently have activities in the MEMS area, a high proportion of which (65 percent) can be classified as "small businesses" (i.e., annual revenues of less than $10 million—in most cases less than $5 million). About 20 large U.S. companies have also incorporated MEMS into their products (e.g., Honeywell, Motorola, Hewlett-Packard, Texas Instruments, Xerox, GM Delco, Ford Motor Company, and Rockwell).

According to Kurt Petersen (1996), a founder of NovaSensor and a recognized pioneer in the field, total sales of MEMS in the United States by 1994 were about $630 million, with pressure sensors for medicine ($170 million), automotive use ($200 million), and industrial/aerospace applications ($200 million) completely dominating the scene. The rest of the market was divided among pressure sensors for non-medical applications ($20 million), accelerometers for air bag deployment ($15 million), auto suspension ($2 million), fuel injectors ($20 million), and microvalves ($2 million). Although developments were anticipated in all of these areas, as well as in wholly new areas, Petersen notes that the pace of commercial development was very slow before the 1990s. MEMS pressure sensors were first commercialized in the 1960s, and ink-jet nozzles in production printers have been evolving since 1974.

In response to the growing interest in MEMS, various trade groups and technical-assessment organizations have surveyed the field and attempted to predict its course. As is customary with predictions and especially with economic punditry, the outcome values of these assessments vary substantially. Although the committee neither reviewed nor compared the various predictions, it did believe that noting some general statements from these sources would be valuable. Projections began to appear in the early 1990s when, for example, a Battelle survey predicted about $8 billion in MEMS products worldwide by the usually quoted target year of 2000. Other predictions since 1990 have generally been more bullish, between $12 and $14 billion.

In 1994, the U.S. trade group SEMI (Semiconductor Equipment and Materials International) conducted a survey of commercial opportunities (Walsh and Schumann, 1994). These predictions were based on information from MEMS manufacturers, users, suppliers, and researchers. This feature does not, of course, validate the study, and committee members had different views of "best guesses" for the field. We repeat here only a few of the SEMI report conclusions starting with its prediction of a year 2000 MEMS world market of more than $14 billion, of which medical and transportation applications for pressure sensing could provide about 30 percent. SEMI's report also predicts major markets (totaling $2.7 billion) for inertial sensors, including accelerometers for auto-crash safety systems, auto suspensions and braking systems, munitions, pacemakers (which can use accelerometers to sense bodily activity), and machine control and monitoring. Other MEMS areas targeted for strong growth in the SEMI survey were fluid regulation and control, optical switching and routing, mass-data storage, displays, and analytical instruments.

Based on a fairly general consensus that lithography-based technologies are the key to low-cost MEMS developments and on the shared desire for "foundry processing," some MEMS foundries are now in operation, notably at MCNC in Research Triangle Park, North Carolina, but also through runs sponsored by the Defense Advanced Research Projects Agency (DARPA) at Analog Devices, Inc., and by special arrangement at Sandia National Laboratories. For specialized uses, such as for space applications, more expensive customized processing techniques like LIGA may be needed, and MCNC is also exploring possibilities in this area. A growing number of examples show that MEMS fabrication could be possible by adding processing steps to conventional IC production lines.

In a recent paper entitled MEMS: What Lies Ahead?, Kurt Petersen (1995) states that "without exception, every company involved in electronics and miniature mechanical components should have programs to familiarize themselves with the capabilities and limitations of MEMS. Instrumentation companies that are not fluent in MEMS in the coming years will experience severely threatening competition." Petersen continues that, as MEMS evolves, it is becoming "less an industry unto itself and more of a critical discipline within many other industries." This means that application-specific MEMS processes will undoubtedly evolve as producers discover the best way to use MEMS for their products. Just like production for ICs, processes for MEMS will probably be limited by economic factors, and designers will attempt to satisfy their needs with the simplest, most economical technology.

The purpose of this report is (1) to review current and projected MEMS needs based on projected applications, (2) to identify shortcomings in present and developing MEMS technologies, (3) to recommend how MEMS can best use advanced materials and fabrication processes to overcome these shortcomings, and (4) to recommend research and development (R&D) areas that would lead to the necessary advances in materials and fabrication processes for MEMS. The first chapter provides background information on the development of the MEMS field and future prospects. Chapter 2 examines the strengths of the various IC-based technologies for fabricating MEMS and their potential for producing even more innovative devices. Chapter 3 focuses on the rationale for introducing new materials and processes that can extend the capabilities and applications of MEMS and that are compatible with IC-based, batch fabrication processes. Chapter 4 extends the discussion of MEMS to the information and manufacturing infrastructure needed to favor the development of MEMS. The final chapter of the report examines the major challenges facing the assembly, packaging, and testing of MEMS.

This report concentrates on MEMS technologies and designs that either derive from or are applicable to those of the IC industry. In the view of the committee, these areas hold the greatest opportunity for the immediate future. Discussions of technologies, fabrication tools, and properties for microsystems made solely from non-IC-based materials (e.g., glasses, plastics, or semiconductors other than silicon) have been necessarily omitted. The committee believes that there are important opportunities for these microsystems, but they are beyond the scope of this report.

Richard S. Muller, chair
Committee on Advanced Materials and
Fabrication Methods for
Microelectromechanical Systems

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Acronyms

A/D	analog-to-digital converter
ADI	Analog Devices, Inc.
AP&T	assembly, packaging, and testing
ASIC	application-specific integrated circuit
BiCMOS	bipolar complementary metal oxide semiconductor
CAD	computer-aided design
CAE	computer-aided engineering
CMP	chemical-mechanical polishing
CNC	computer numerical control
CPU	central processing unit
CRT	cathode-ray tube
CVD	chemical vapor deposition
DARPA	Defense Advanced Research Projects Agency
DIP	dual in-line package
DLP	digital light processing
DMD	digital micromirror display
DRAM	dynamic random-access memories
DRIE	deep reactive ion etching
EDM	electron-discharge machining
FAMOS	field-avalanched metal oxide semiconductor device
FEA	finite-element analysis
HF	hydrofluoric acid
HP	Hewlett-Packard
IBSD	ion-beam sputter deposition
IC	integrated circuit
ICP	inductively coupled plasma
KOH	potassium hydroxide
LCD	liquid-crystal display
LED	light-emitting diode
LPCVD	low-pressure chemical-vapor deposition
MBE	molecular-beam epitaxy
MEMS	microelectromechanical systems
MOCVD	metal-organic chemical-vapor deposition
MOD	metal/organic decomposition

MOS	metal oxide semiconductor
MOSIS	metal oxide semiconductor implementation system (now refers to a wider scope of technologies)
MST	microsystem technology
NITINOL	Ni/Ti thin-film material
NMOS	N-channel metal oxide semiconductor
NSF	National Science Foundation
NVFRAM	nonvolatile ferroelectric random access memory
PCA	portable clinical analyzer
PLAD	pulsed laser-ablation deposition
PECVD	plasma-enhanced chemical-vapor deposition
PMMA	polymethylmethacrylate
PSD	plasma sputter deposition
R&D	research and development.
RIE	reactive-ion etching
SAM	self-assembled monolayer
SMA	shape memory alloy
TI	Texas Instruments
TO	transistor outline
VLSI	very large-scale integration

Executive Summary

As the twenty-first century approaches, the capacity to shrink electronic devices while multiplying their capabilities has profoundly changed both technology and society. Beginning in 1948, the vacuum tube gave way to the transistor, which was followed by a series of major strides leading to integrated circuits (ICs), which led to on-chip electronic systems, such as large-scale memories and microprocessors. Present silicon very-large-scale-integrated (VLSI) chip technology seems destined to continue developing for at least another 20 years based on smaller and smaller electronic devices that can operate faster and do more.

In the late 1980s, the design and manufacturing tool set developed for VLSI was adapted for use in a field called microelectromechanical systems (MEMS). These systems interface with both electronic and nonelectronic signals and interact with the nonelectrical physical world as well as the electronic world by merging signal processing with sensing and/or actuation. Instead of handling only electrical signals, MEMS also bring into play mechanical elements, some with moving parts, making possible systems such as miniature fluid-pressure and flow sensors, accelerometers, gyroscopes, and micro-optical devices. MEMS are designed using computer-aided design (CAD) techniques based on VLSI and mechanical CAD systems and are typically batch-fabricated using VLSI-based fabrication tools. Like ICs, MEMS are progressing toward smaller sizes, higher speeds, and greater functionality.

MEMS already have a track record of commercial success that provides a compelling case for further development (e.g., pressure sensing, acceleration sensing, and ink-jet printing). Like any developing field, however, commercial successes in the MEMS field coexist with products still under development that have not yet established a large customer base (e.g., MEMS display systems and integrated chemical-analysis systems).

The U.S. Department of Defense and the National Aeronautics and Space Administration requested that the National Research Council conduct a study (1) to review current and projected MEMS needs based on projected applications, (2) to identify shortcomings in present and developing MEMS technologies, (3) to recommend how MEMS can best use advanced materials and fabrication processes to overcome these shortcomings, and (4) to recommend research and development areas that would lead to the necessary advances in materials and fabrication processes for MEMS. The Committee on Advanced Materials and Fabrication Methods for Microelectromechanical Systems, under the auspices of the National Materials Advisory Board, was convened to undertake this study and write this report.

The committee concluded that the MEMS field faces a number of challenges to the establishment of an environment that promotes healthy and vigorous growth. These challenges are presented in this Executive Summary along with recommendations for meeting them. Because of the broad perspective with which the MEMS field is viewed in the report, the findings and recommendations are not prioritized.

LEVERAGING AND EXTENDING THE INTEGRATED CIRCUITS FOUNDATION

A great deal of the excitement and promise of MEMS has arisen from the demonstrated ability to produce three-dimensional fixed or moving mechanical structures using lithography-based processing techniques derived from the established IC field. Conventional IC materials can continue to be used in new ways in MEMS, and much of the needed MEMS-specific hardware can still be leveraged from IC-technology. Such MEMS developments are most likely to be accepted in traditional IC-fabrication facilities and therefore most likely to succeed commercially.

In the microelectronics world, major steps forward have sometimes resulted from inspired looks backward at technologies and materials that were already known and well categorized. For MEMS, this "cleverness research" can take on a special character by posing mechanical problems to technologies that originally responded only to the demands of electrical design. A wide field of opportunity for creative work in MEMS could be based on what is already known about IC processing, particularly in the re-evaluation of the vast knowledge compiled during the history of IC development (e.g., transistor-transistor logic; integrated-injection logic; analog; bipolar; n-channel metal-oxide semiconductors).

Conclusion. The expertise and advanced state of the current microelectronics industry provides an enormous advantage for the development of MEMS. Leveraging and extending existing IC tools, materials, processes, and fabrication techniques is an excellent strategy for producing MEMS with comparable levels of manufacturability, performance, cost, and reliability to those of modern VLSI circuits.

Recommendation. Efforts to stimulate solutions to the challenges of producing MEMS should capitalize on the families of relatively well understood and well documented IC materials and processes. These solutions may be found in current IC practices but may also result from creatively re-establishing older IC technologies. This recommendation calls for continuing strategic investment.

ENLARGING THE SUITE OF MATERIALS SUITABLE FOR INTEGRATED-CIRCUIT-LIKE PROCESSING

Although there may be commercial advantages to leveraging the present suite of IC-process materials, they will not be able to meet all of the demands that a growing number of users and applications will place on MEMS. Easily foreseen requirements (e.g., higher forces, stability in harsh and high-temperature environments, and robust high-aspect-ratio structures) will compel the application of new materials and extend the MEMS field beyond the boundaries of the IC world.

Materials that are not usually used in IC processes include magnetic, piezoelectric, ferroelectric, and shape-memory materials. Actuating-force requirements for valve closures and motor drives, for example, are already drawing attention to the advantages these materials would bring to MEMS. Other developments, such as MEMS for optics, biological purposes, chemical-process controls, high-temperature applications, and other hostile environments, will inevitably draw attention to the need for an even broader range of materials.

In the IC world, new materials are typically incorporated as thin films and are produced by a limited number of techniques (e.g., low-pressure chemical-vapor deposition or sputtering). Many of these materials either do not show optimal mechanical properties in thin-film form or are difficult to deposit by typical IC-fabrication methods or are incompatible with the microelectronic IC process. For some MEMS designs, it is possible to apply these specialized materials either by incorporating them in a step prior to more-conventional processing or by adding them as a final step. Either option raises the possibility that the technology will be substantially different from better known processing techniques. Materials that are incompatible with the IC-processes might have to be handled by a specialized foundry.

Conclusion. Extending the list of materials that have useful MEMS properties and can be processed using lithography-based, IC-compatible techniques will be beneficial to MEMS development.

Recommendation. Research and development should be encouraged to develop new materials that extend the capabilities of MEMS. The new materials should be integrable, at some level, with conventional IC-based processing. This recommendation calls for continuing strategic investment.

Recommendation. Research should be encouraged to develop techniques to produce repeatable, high-quality, batch-processed thin films of specialized materials and to determine the dependence of their properties on film-preparation techniques. For some materials, it may be advisable to establish "foundries" that are available to the entire MEMS community and can serve as repositories for equipment and know-how. This recommendation calls for new strategic investment.

CHARACTERIZING MEMS MATERIALS

The IC industry has been built on an extensive, constantly expanding body of knowledge about the behavior of silicon and related materials as they are scaled down in size. No comparable resource has been established for MEMS, however. For example, although a great deal is known about the electrical properties of polysilicon thin films, not much is known about their micromechanical properties or about specific details of the long-term reliability of mechanically stressed polysilicon or the surface mechanics related to friction, wear, and stress-related failure. There is a similar lack of fundamental knowledge about other thin-film materials borrowed from the electrical domain that are now exercised mechanically (e.g., silicon nitride, silicon dioxide, and thin-film metals). Many thin-film materials that are used in the IC industry (e.g., aluminum, silicon dioxide, amorphous silicon, porous silicon, various other deposited and plated metals, and polyimide) have still not been extensively studied and evaluated for their applicability to MEMS.

Conclusion. A thorough understanding of the micromechanical properties of the materials to be used in MEMS at appropriate scales is not available.

Recommendation. The characterization and testing of MEMS materials should be an area of major emphasis. Studies that address fundamental mechanical properties (e.g., Young's modulus, fatigue strength, residual stress, internal friction) and the engineering physics of long-term reliability, friction, and wear are vitally needed. It is important that these studies take into account fabrication processes, scaling, temperature, operational environment (i.e., vacuum, gaseous, or liquid), and size dependencies. Studies of the size effects of physical elements, on a scale comparable to the crystallite regions in a polycrystalline material, are required. This recommendation calls for continuing strategic investment.

UNDERSTANDING SURFACE AND INTERFACE EFFECTS

The properties of materials can differ at the small scales at which individual MEMS devices are configured, causing effects that can influence their behavior. At these tiny scales, material behavior is more influenced by surface-driven effects than by volume or bulk effects. For example, frictional effects take on overwhelming importance, in contrast to inertial effects, in small mechanical systems. If the interfaces act as electrical contacts (e.g., in MEMS microrelays), additional wear, corrosion, frictional effects, and contact forces are present. Surface-to-surface sticking (stiction) is also likely to be important in surface-driven processes. During the drying process and after the final cleaning of MEMS devices, the surface tension of the meniscus of liquids can pull suspended mechanical structures toward nearby surfaces, causing the structures to become stuck. Stiction can also occur during the operation of actuated MEMS if shock, electrostatic discharge, or other stimuli cause moving components to touch either each other or to touch another surface.

The MEMS operating environment and the interfaces of this environment on individual MEMS devices can influence performance. Signals admitted to the MEMS package may have electrical, thermal, inertial, fluid, chemical, optical, and possibly other origins. Output can be electrical, optical, mechanical, chemical, hydraulic, or magnetic signals. MEMS applications to liquid systems, for example, would raise interface questions about the use of wetting and dewetting agents and the nature of fluids in micrometer-sized channels and cavities. The high precision of some MEMS sensing devices also makes them sensitive to gas/solid interactions.

Conclusion. Further development of moving elements in MEMS demands a more complete understanding of (1) the effects of internal friction, Coulomb friction, and wear at solid/solid interfaces and (2) the influence of interfaces on performance and reliability. This understanding should lead to the development of suitable coatings, lubricants, and wetting agents, as well as improved designs that take these effects into account.

Recommendation. Surface and interface studies should be pursued to address questions associated with contact forces, stiction, friction, corrosion, wear, lubrication, electrical effects, and microstructural interactions at solid, liquid, and gaseous interfaces. Engineering design and manufacturing solutions to the problems associated with MEMS surfaces and interfaces should also be pursued. This recommendation calls for continuing strategic investment.

ETCHING TECHNOLOGIES

At the heart of MEMS is the ability to construct extremely small mechanical devices, preferably using batch processing. Wet etching has historically dominated the MEMS field because (1) structures can be micromachined from silicon in a short time and (2) chemical-etch equipment is well established, simple, and inexpensive. The disadvantages of wet-chemical processing are its inability to achieve vertical sidewalls and nonorthogonal linear geometries in d silicon and its reaction with films on the wafer surface. Because of the lateral spread of etching, patterned features must also be spaced relatively far apart so that adjacent features do not merge, and the features on the mask and pattern-transfer layer must be biased or reduced (and sometimes even distorted) to achieve the desired size and shape at the completion of the wet-etch process. Although dry etching is a mainstay of IC processing and gas-phase dry-etching techniques are currently a subject of research for MEMS production, the etch depths for MEMS are often significantly greater than those commonly employed in IC-fabrication. Therefore, etching for MEMS may present different or additional challenges.

Conclusion. Because controlled etching is so important to the fabrication of three-dimensional structures and, therefore, to progress in MEMS, methods of etching in a controlled fashion and ways of tailoring the isotropic or anisotropic etch-rates of various materials are of great value.

Recommendation. Further research and development should be undertaken to improve etches, etching, and etching controls for MEMS. This work should take into account the status, potential development, and limitations of manufacturing-process equipment. This recommendation calls for continuing strategic investment.

ESTABLISHING STANDARD TEST DEVICES AND METHODS

Standard test devices and methods are required to determine the mechanical properties of MEMS devices, to demonstrate the repeatability and reliability of mechanical devices, and to facilitate quality-control practices. Package-level testing is currently the most common way to measure MEMS performance, but the development of in-process wafer-level testing will be necessary for low cost manufacturing. Wafer-level testing of MEMS presents special challenges that are often product dependent. Nevertheless, generic test structures that indicate basic mechanical properties of MEMS materials at the wafer level should be developed and characterized. As more and more industries, universities, and other research groups enter the MEMS field, it is also becoming increasingly important to provide accepted standards that can be used for comparison.

Conclusion. Test-and-characterization methods and metrologies are required to (1) help fabrication facilities define MEMS materials for potential users, (2) facilitate consistent evaluations of material and process properties at the required scales, and (3) provide a basis for comparisons among materials fabricated at different facilities.

Recommendation. Standard test methods, characterization methods, and test devices should be developed and disseminated that are suitable for the range of materials and processes of MEMS. Ideally, metrology structures will be physically small, simply designed, easily replicated, and conveniently and definitively interrogated. MEMS engineering standards should be similar to those already established for materials and devices in conventional sizes by organizations such as the National Institute of Standards and Technology (NIST), the American Society for Testing and Materials (ASTM), and the Institute of Electrical and Electronics Engineers (IEEE). This recommendation calls for new strategic investment.

MEMS PACKAGING

Packaging a device, interfacing it to its operating domain, and assembling it as a part of a larger system are critical final production steps and can easily represent up to 80 percent of the cost of a component. Although considerable attention continues to be paid to innovative applications of MEMS processing techniques and devices, "back-end" processes have historically been approached on a specialized, case-by-case basis. The lack of publicly available technology or information to support packaging has meant that each organization has essentially had to invent and reinvent solutions to common problems. Possible extensions of batch processing to back-end processes could substantially reduce costs.

Conclusion. Packaging, which has traditionally attracted little interest compared to device and process development, represents a critical stumbling block to the development and manufacture of commercial and military MEMS. The imbalance between the ease with which batch-fabricated MEMS can be produced and the difficulty and cost of packaging them limits the speed with which new MEMS can be introduced into the market. Expanding the small knowledge base in the packaging field and disseminating advances aggressively to workers in MEMS could have a profound influence on the rapid growth of MEMS.

Recommendation. Research and development should be pursued on MEMS packaging and assembly into useful engineering systems. The goal should be to define, insofar as possible, generic, modular approaches and methodologies and to extend batch-processing techniques into the various back-end steps of production. This recommendation calls for new strategic investment.

FOUNDRY AND COMPUTER-AIDED DESIGN INFRASTRUCTURE FOR MEMS

Rapid development in the IC industry has been aided by the establishment of a foundry infrastructure that ensures that industry and government users will be able to manufacture IC products at competitive rates and enables companies that do not have wafer-processing capabilities to enter the field. One of the key factors in the development of the IC foundry infrastructure was the development of a CAD infrastructure that became the backbone of foundry operations. Design methods were implemented that allowed IC designers to develop systems independently and have them manufactured by submitting only a design-language file. The MEMS field is more complicated because of the broad range of electrical and mechanical applications, including consumer, automotive, aerospace, and medical products. Thus, several standard-process MEMS foundries would have to be available and accessible, as well as custom, flexible fabrication facilities for users who require access and manipulation of the process to produce and optimize their products.

The committee recognizes that realizing the concept of MEMS foundries may be difficult because many commercial companies have difficulty seeing "what's in it for them." Besides the danger of compromising proprietary know-how, companies offering a foundry service will have to commit to specific processes and reasonable turnaround schedules. In the instances where small industries have tried to accommodate MEMS foundry runs so far, the results have not been warmly received. A more feasible road to at least moderate success at the present juncture appears to be using academic and government laboratories to provide foundry services. The recent expansion of the National Nanofabrication Laboratory to sites at several universities and the capabilities of national laboratories, like Sandia and Livermore, may provide opportunities for MEMS foundries of a different nature, where direct hands-on work can be done by the MEMS researcher. This kind of operation could not be as widely extended as the more traditional foundry approach of MCNC, which interacts with users only through exchanges of software, but it may provide an interim avenue until specific areas in the MEMS field are further developed.

Conclusion. Establishing standard CAD and foundry infrastructures for MEMS is essential in the near future to support the growth of MEMS from the prototype and low-volume commercial level to the volume-driven, low-cost commercial level. The development of a MEMS foundry-technology base, similar to the base that supports ICs, would ensure that MEMS products could be manufactured at competitive rates and would enable more small companies and research organizations to enter the field.

Recommendation. A MEMS CAD-infrastructure that extends from the processing and basic modeling areas to full system-design capabilities should be established. A process-technology infrastructure (e.g., supporting electrical, mechanical, fluid, chemical, and other steps and their integration to form complete systems) that is widely available to MEMS designers and product engineers should be developed. This recommendation calls for new strategic investment.

ACADEMIC STRUCTURE TO SUPPORT MEMS

The field of MEMS rests on multidisciplinary foundations. Practitioners who are poised to advance MEMS must have knowledge and skills in several fields of engineering and applied sciences. The participation of motivated, well trained young researchers is probably the single most important driver for success in MEMS. Some of these researchers will come from the ranks of trained IC engineers, who are already familiar with tools, materials, and procedures that are useful for MEMS. In general, however, these practicing engineers will have to learn new aspects of mechanical design, materials behavior, computing techniques, and systems design. Providing learning opportunities and educational materials for practicing engineers is important. But for future engineering students, effective instruction in MEMS will require major changes in curricula. A high priority should be placed on establishing an academic infrastructure that conveys the excitement and promise of the field, offers a sound and thorough education for MEMS researchers, and facilitates development of and access to new and innovative ideas across and among various disciplines.

Conclusion. Contributors to MEMS can be recruited both from practitioners already active in the IC field and from newly trained engineers. To facilitate the entry of practicing engineers into the field, opportunities to learn material that is special to MEMS should be encouraged through stimulating short courses and specialized text materials. For engineering undergraduates entering MEMS, programs and industrial procedures should be encouraged that stimulate multidisciplinary university education and enhance the skill and knowledge base of those training for or contributing to the development of MEMS. New MEMS engineers will require a broad understanding of several fields (e.g., electrical, mechanical, materials, and chemical engineering).

Recommendation. MEMS short courses and instructive materials that introduce practicing IC engineers to MEMS should be encouraged. Teaching institutions should be encouraged to see the benefits to their students and to their programs of emphasizing a broad, basic foundation in materials, production techniques, and engineering needed for MEMS. This recommendation calls for new strategic investment.

1

Background

As we approach the twenty-first century, the continuous ability of engineers to shrink electronic devices while simultaneously increasing their performance has profoundly affected both technology and society. A half-century ago, the transistor ushered in the solid-state era of electronics and began a procession of events that drove most earlier technologies (based on vacuum tubes) from the field. In a series of major strides, silicon became the material of choice, planar processing was introduced to make photolithography possible, and the integrated circuit (IC) was born. The planar-processed IC is, without question, a great engineering achievement, making possible the low-cost production of a myriad of electrical systems, including the memory chip and the microprocessor. Silicon very large scale integrated (VLSI) chip technology seems destined to continue the trend toward smaller sizes, higher performance, and greater functionality for at least another 20 years.

The success of solid-state microelectronics ignited the spark of a similar revolution in microscopic systems in the nonelectronic world and resulted in the adaptation of the VLSI tool-set to the manufacture of systems that interface with the nonelectrical environment. Research in this field began in the 1950s with breakthrough studies on piezoresistance in silicon. Single-crystal silicon's piezoresistance and elastic behavior made it an excellent material for the production of sensing devices and led in the 1960s to the development of the first silicon pressure sensors. In the 1970s, the field grew as pressure-sensor production increased and the first silicon accelerometers were developed. The field was dubbed MEMS (microelectromechanical systems) in the late 1980s after silicon fluid valves, electrical switches, and mechanical resonators were developed and marketed (see Box 1-1).

MEMS contain mechanical elements that are built on such a small scale that they can be appreciated only with a microscope. MEMS elements interface with nonelectronic signals and often merge signal processing with sensing and/or actuation. MEMS may contain mechanical parts, such as pressure sensors, flow sensors, or optical-beam handling devices. Some fully integrated MEMS are designed using computer-aided design (CAD) techniques based on VLSI and mechanical CAD systems; they are batch-fabricated using VLSI-based fabrication tools. Like VLSI, MEMS are becoming progressively smaller, faster, and more functional.

The U.S. Department of Defense and the National Aeronautics and Space Administration requested that the National Research Council conduct a study (1) to review current and projected MEMS needs based on projected applications, (2) to identify shortcomings in present and developing MEMS technologies, (3) to recommend how MEMS can best use advanced materials and fabrication processes to overcome these shortcomings, and (4) to recommend research and development (R&D) areas that would lead to the necessary advances in materials and fabrication processes for MEMS. The Committee on Advanced Materials and Fabrication Methods for Microelectromechanical Systems was convened, under the auspices of the National Materials Advisory Board, to conduct this study and write this report.

The MEMS track record already includes several commercial successes (e.g., pressure sensors, accelerometers, and ink-jet print-heads) that provide a compelling case for further development. Like any other developing field, MEMS' commercial successes coexist with less mature products that have yet to establish a customer base (e.g., optical-mirror arrays for display purposes, microphotonic switching devices, actuated

BOX 1-1
Semantics: What's in a Name?

In the early 1980s, a general consensus was reached about creating microsystems, and many names for the emerging field were coined. Not surprisingly, they met with varying degrees of acceptance, and, also not surprisingly, the names were not consistent internationally (even if all of them were in English). Several names began to dominate:

- microsystem technologies (MST)
- micromechatronics
- microdynamic systems
- micro total analysis systems (μ-TAS)
- microelectromechanical systems (MEMS)

The two most resilient names are microsystem technologies and microelectromechanical systems with their respective acronyms, MST and MEMS. The preferred label in the United States is MEMS, whereas MST is used in Europe and, to a lesser extent, in Japan. To some observers, these choices reflect a stronger emphasis on *technologies* in Europe and Japan and a stronger focus on *systems* in the United States.

gas-flow microvalve systems, and microbiological systems). There have also been several programs aimed at the commercial development of MEMS that have been discontinued, including those supporting automotive fuel-injection manifold air-pressure-sensing MEMS, because they were not found to be cost effective. In other applications, such as microvalving and suspension control, the adoption of MEMS has been slow. Displays based on MEMS, such as the mirror-array by Texas Instruments (described below), also face intense competition from newly developed liquid-crystal designs. Although many observers regard these developments as normal growing pains for a new technology, others have serious reservations about the future of the field.

The remainder of this chapter presents an overview of current trends in the MEMS market. The chapter is divided into three sections. The first section describes MEMS that are already successful on the market, such as thermal ink-jet print-heads and accelerometers. The second section reviews MEMS technologies currently under development that show significant commercial potential, such as chemical-sensor arrays and display technologies based on mechanical reflecting elements. The third section discusses some future possibilities and long-range research opportunities.

COMMERCIAL SUCCESSES

Although most people still consider MEMS a technology of the future, a considerable number of people already use MEMS-based devices every day. The ink-jet cartridges in many commercial printers and many of the accelerometers used to deploy air bags in cars are MEMS devices. This section examines the commercial success of ink-jets and accelerometers.

Thermal Ink-Jet Printing

The thermal ink-jet print-head is the largest commercial success story for MEMS technology in terms of both unit sales and dollar amounts. Thermal ink-jet cartridges currently dominate the ink-jet printing market and account for well over a billion dollars per year, independent of the printers in which they are used. Ink-jet printers (both thermal and piezoelectric) typically cost less initially than dry-toner laser printers and, despite their slower speed and higher per-page cost, are often the solution of choice for low-volume print runs. Vendors of ink-jet printers include Canon, Epson, Hewlett-Packard (HP), Lexmark (formerly a part of IBM), and Xerox.

The concept of drop-on-demand thermal ink-jet printing was developed independently, and nearly simultaneously, by HP and Canon. HP commercialized the "Thinkjet" in 1984 using a glass substrate, while Canon commercialized its version as the "Bubblejet." Later print-heads used silicon

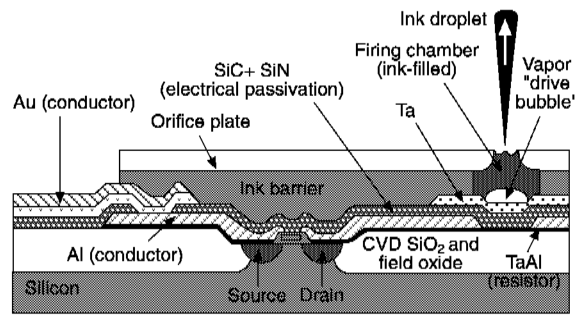

FIGURE 1-1 Cross-section of an integrated thermal ink-jet chip. This instantaneous view shows an ink droplet being ejected from the firing chamber by the "drive bubble" created by resistive heating. An NMOS (N-channel metal oxide semiconductor) transistor is associated with each firing chamber. Transistor addressing is achieved by a row-column address scheme. Source: Adapted from Beatty, 1996.

substrates to take advantage of the widely available equipment set and fabrication methods for silicon.

Thermal ink-jet print-heads (or pens) are packaged as replaceable drop-in cartridges on the order of 9 to 50 cm^3 in volume. They usually comprise a supply of ink and an array of microscopic heating resistors on a silicon substrate mated to a matching array of ink-ejection orifices (Barth, 1995). In some designs, the associated active electronics are on the same substrate. These pens constitute the enabling technology-base for printers ranging from battery-powered, portable units to large-format bed plotters. Figure 1-1 shows a cross-section of a thermal ink-jet head with integrated active electronics. The orifice plate of the print head is made of plated nickel laminated on top of a polymer barrier layer. Although producing this arrangement requires a departure from purely lithographic batch processing, the lamination process has been demonstrated to be cost effective for the large volumes demanded by the ink-jet market.

Figure 1-2 illustrates the decrease in ink-drop weight over time for one family of ink-jet printers. Image quality is greatly

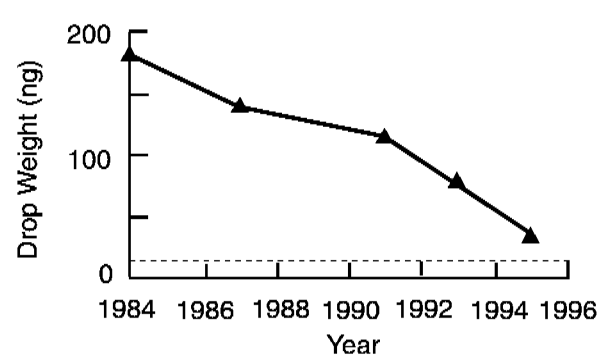

FIGURE 1-2 Evolution of ink-jet drop weight versus time. Drop weights below the dotted line can produce photographic-quality images. Source: Beatty, 1996.

influenced by ink-drop weight. The horizontal dotted line in the figure represents the minimum drop-size the human eye can perceive. Drop weights below this threshold can produce photographic-quality images. Ink-jet printing thus has the potential to replace silver halide film as a medium for photographic prints. This prospect is expected to cause some dislocations in the photographic industry as electronic cameras that can be easily interfaced with computers and printers begin to produce high-quality graphics for presentations and other uses. Ink-jet technology is also being studied for possible use in the deposition and patterning of sensitive biochemicals (e.g., clinical-assay reagents) in the production of biomedical devices.

Ink-jet technology has evolved, for the most part, via internal investment by commercial companies. These investments have already reaped significant benefits in the marketplace. Approximately 67 million ink-jet printers were in existence worldwide as of 1995 (Barth, 1995). This large base of printers promises a dependable revenue stream for vendors of disposable ink-jet pens. Customers can expect continued improvement in print quality and speed at a reasonable cost.

Accelerometers

Government mandates for passive-restraint devices in automobiles created a large market for air bags (i.e., passive restraint devices in which an explosive gas-generating charge is triggered by an electrical signal from a crash sensor). MEMS technology has been adapted to this market because it promises high reliability, ruggedness, and cost effectiveness. Several MEMS technologies have vied for the crash-sensor market, which requires both self-testing (for reliability) and accurate, rapid, acceleration sensing (for decision making). Developers in the United States include Analog Devices, Inc., Delco Electronics, Ford Motor Company, General Motors, EG&G IC Sensors, NovaSensor, and Motorola. A large producer in Europe is SensoNor of Norway.

The largest market penetration thus far for board-mountable integrated accelerometers has been achieved by Analog Devices and SensoNor. These companies took very different approaches to the design of crash sensors. Analog Devices used single-chip bipolar-complementary metal-oxide-semiconductor (Bi-CMOS) processing (e.g., the ADXL50); SensoNor employed a two-chip approach (e.g., the SA30).

The Analog accelerometer is based on techniques that were originally developed at the University of California at Berkeley in the early 1980s. These techniques reached their present level of sophistication via continued R&D investment by academia, industry, and government. The accelerometer chip employs a suspended polycrystalline-silicon seismic mass tethered by four polysilicon beams to the substrate at their distal ends (Figure 1-3). Fingers extend laterally from the movable seismic mass perpendicular to the sensitive axis. Other fingers fixed to the substrate reach between the

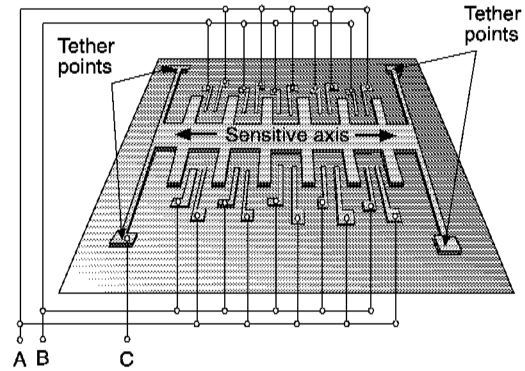

FIGURE 1-3 Schematic illustration of the sensing element of the ADXL50 accelerometer. Source: Analog Devices, Inc.

movable set and apply coulombic force when voltages are applied between terminals A, B, and C. The voltage required to hold the seismic mass motionless relative to the static fingers provides the acceleration signal. This "force-balanced system" uses a precision measurement method that is well established but typically available only in very expensive systems. The sensing element is the heart of an accelerometer chip (Figure 1-4) but occupies less than 1 mm^2 on a chip that is 9 mm^2 in area. The sensing element can be combined with a Bi-CMOS electronics fabrication process with only moderate increases in complexity, which means the combined sensor and circuit on one silicon chip can be produced at low cost.

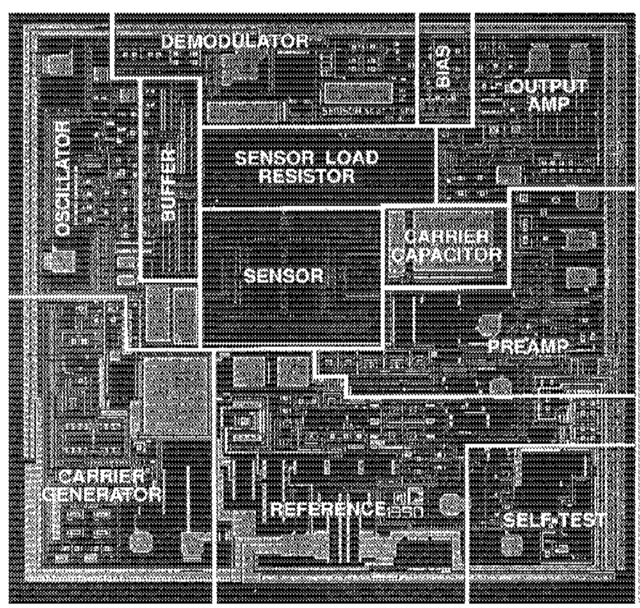

FIGURE 1-4 Annotated photomicrograph of an ADXL50 single-chip accelerometer. The sensing element in the center is surrounded by active electronics. The motion-sensitive direction lies in the plane of the chip and is the vertical axis in this photograph. Chip size is 3 mm x 3 mm. Source: Analog Devices, Inc.

The SensoNor accelerometer sensing element is a single-crystal resonant beam that bridges a cavity in a silicon chip. Stress on the beam from acceleration perpendicular to the plane of the chip causes a change in the resonant frequency. This frequency change is detected by electronics contained on a separate chip, and a signal is emitted to deploy the air bag. The sensing and electronics chips are packaged together in a single surface-mounted package. Several other concepts for accelerometers (e.g., Ford Motor Company's silicon-on-glass torsional accelerometer [Spangler and Kemp, 1995] and Motorola's family of silicon capacitive micromachined accelerometers [Ristic et al., 1993]) also rely on dual-chip approaches (e.g., Figure 1-5).

These two device types have not yet reached the automotive market in large quantities. Like SensoNor, these companies have decided that their cost and performance goals can be met at this time by combining a simple sensing chip with a separate electronics chip. It appears that several approaches to crash sensing are suitable from a performance perspective so that cost considerations alone are likely to dictate which ones dominate the market in the long run.

NEWLY INTRODUCED PRODUCTS

High-resolution displays and chemical-sensor arrays are two examples of emerging MEMS products with the potential for strong market growth.

High-Resolution Displays

Displays have long been dominated by cathode-ray tubes (CRTs) and liquid-crystal display (LCD) monitors. CRTs are

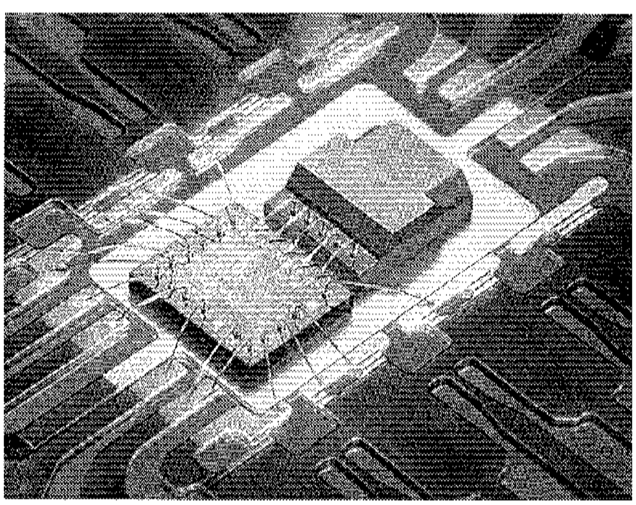

FIGURE 1-5 Motorola accelerometer chip (upper right) and electronics chip (lower left) packaged together on a metal lead frame. The sensitive direction is perpendicular to the upper surface of the accelerometer chip. Source: Motorola.

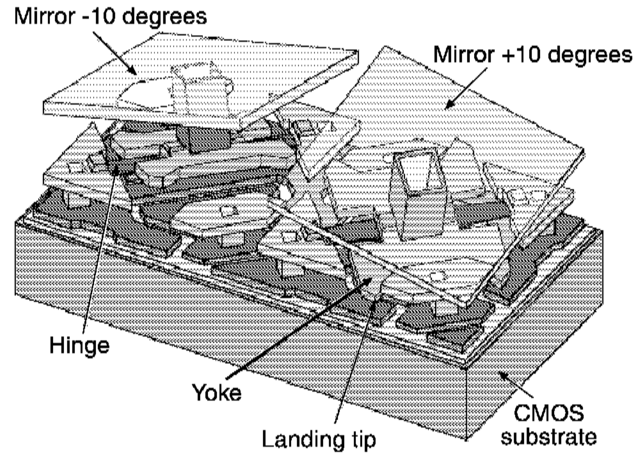

FIGURE 1-6 Two pixels in the Texas Instruments mirror array. Mirrors are shown as transparent. Source: Hornbeck, 1997.

typically too large and too bulky for portability and are limited in screen size by several factors including the need to support an internal vacuum against atmospheric pressure. Although LCDs have traditionally been limited in brightness, contrast, speed, and resolution, they have improved greatly with recent LED (light-emitting-diode)-LCD projection displays. As a result, the LCD market has been expanding.

Mirror-array technology is a revolutionary new technique made possible by MEMS. Mirror arrays show promise for the production of large, lightweight, high-brightness, high-contrast, and high-resolution displays at reasonable cost. Texas Instruments (TI), aided by U.S. government R&D funds, has dedicated more than a decade to the development of array-micromirror technology for video, computer, and presentation displays. TI calls its approach digital light processing (DLP) and its basic device a digital micromirror display (DMD). The DMD consists of many tiltable mirrors and associated circuitry that are batch-fabricated on a single silicon chip. The mirrors are individually addressed and tilted by coulombic force either toward or away from a collimating lens that collects the light to be projected on the display screen. Each mirror is electrostatically deflected by electrodes beneath it (Figure 1-6). The mirrors, which are less than 20 m on an edge, are closely spaced to give a maximum "fill factor" and make as much of the chip area a reflecting surface as possible (Figure 1-7). Gray scale is provided by varying the percentage of time each mirror directs light to the display screen. Either one color wheel or three separate chips provide multilevel color capability. The first DMD micromirror (and hence pixel) arrays have 800 x 600 pixels per chip.[1] Chips with 1024 x 768 pixels are currently under development (Hornbeck, 1996).

[1]These chips have recently been introduced on the market in projection displays, such as the InFocus LitePro 620 projector.

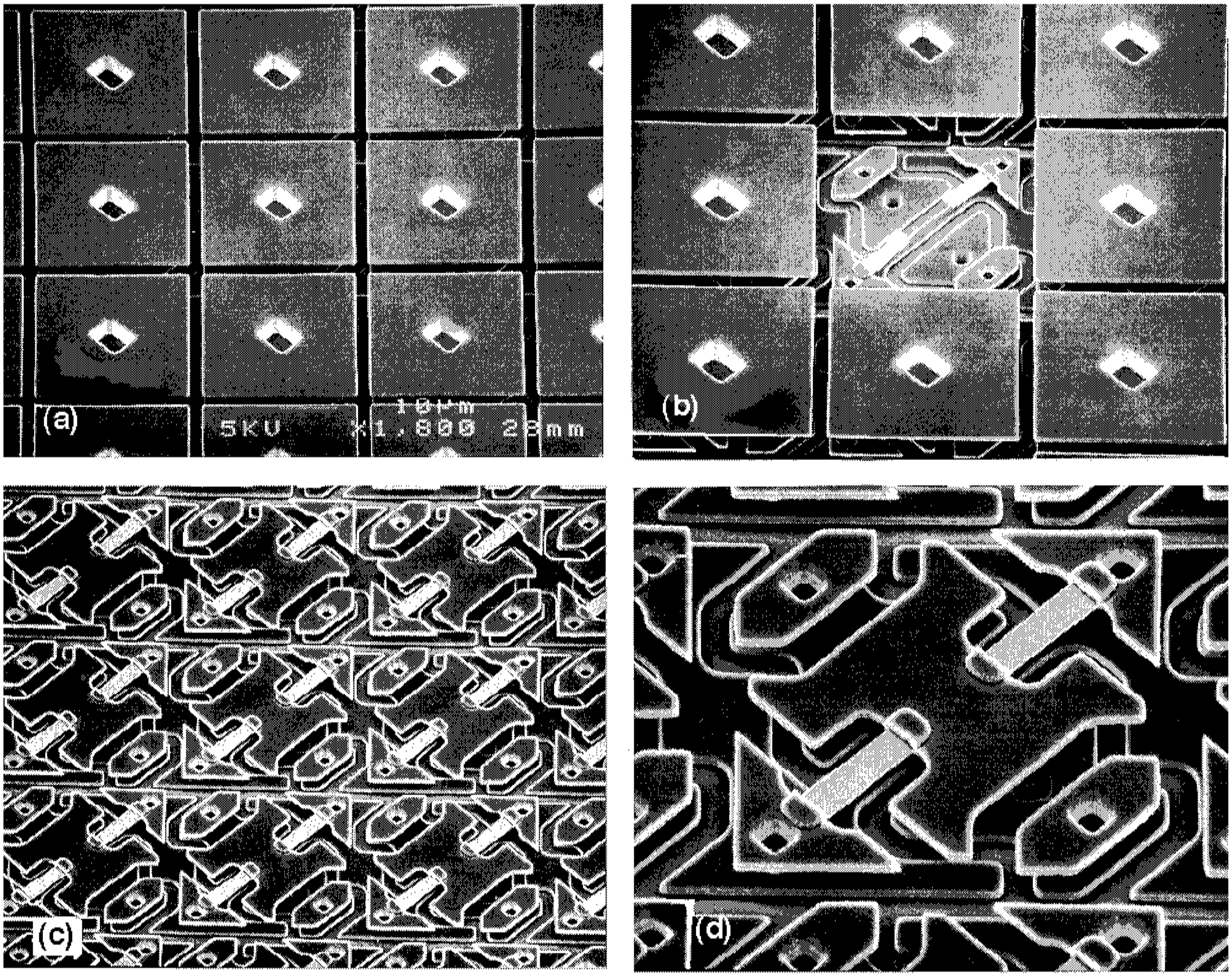

FIGURE 1-7 Scanning electron photomicrographs: (a) completed digital mirror display (DMD) chip; (b) completed DMD chip with mirror layer and yoke-and-hinge layer removed for one pixel; (c) completed DMD chip with mirror layer removed; (d) close-up of one pixel with mirror layer removed. Source: Hornbeck, 1995.

Alternative MEMS display technologies are under industrial development elsewhere (e.g., Silicon Light Machines in the United States and Daewoo in Korea), but dates for their commercial introduction are still uncertain.

Chemical-Sensing Arrays

The high cost associated with diagnostic testing is endemic to the cost of health care. MEMS technology can provide rapid, disposable, inexpensive, and reliable testing that requires small sample sizes and is suitable for use at bedsides or in doctors' offices. A growing number of companies have significant programs under way to produce MEMS for chemical sensing that will reduce the cost and improve the quality of testing (e.g., Affymetrix, Perkin-Elmer Applied Biosystems, and Caliper). The objective of these programs is to develop systems that offer one or more of the following improvements: higher throughput, lower cost per test (either by minimizing materials requirements or complexity), or field portability.

The first chemical sensor-chips have only recently come onto the market in a portable format configuration and have yet to return sizable profits to manufacturers. For example, the i-STAT portable clinical analyzer (PCA) is a hand-held unit that can analyze 60 μL of whole blood using disposable cartridges. The PCA employs micromachined electrochemical sensors (biosensors) to measure sodium, potassium, and chloride ions, as well as urea, glucose, and hematocrit concentrations. The heart of the i-STAT system is a disposable cartridge, which includes a molded frame with an entry for samples and calibration reagents that are distributed to the sensors located in the hand-held reader. The system measures 20 x 6.5 x 5 cm, weighs 539 g, and is powered by two 9V batteries.

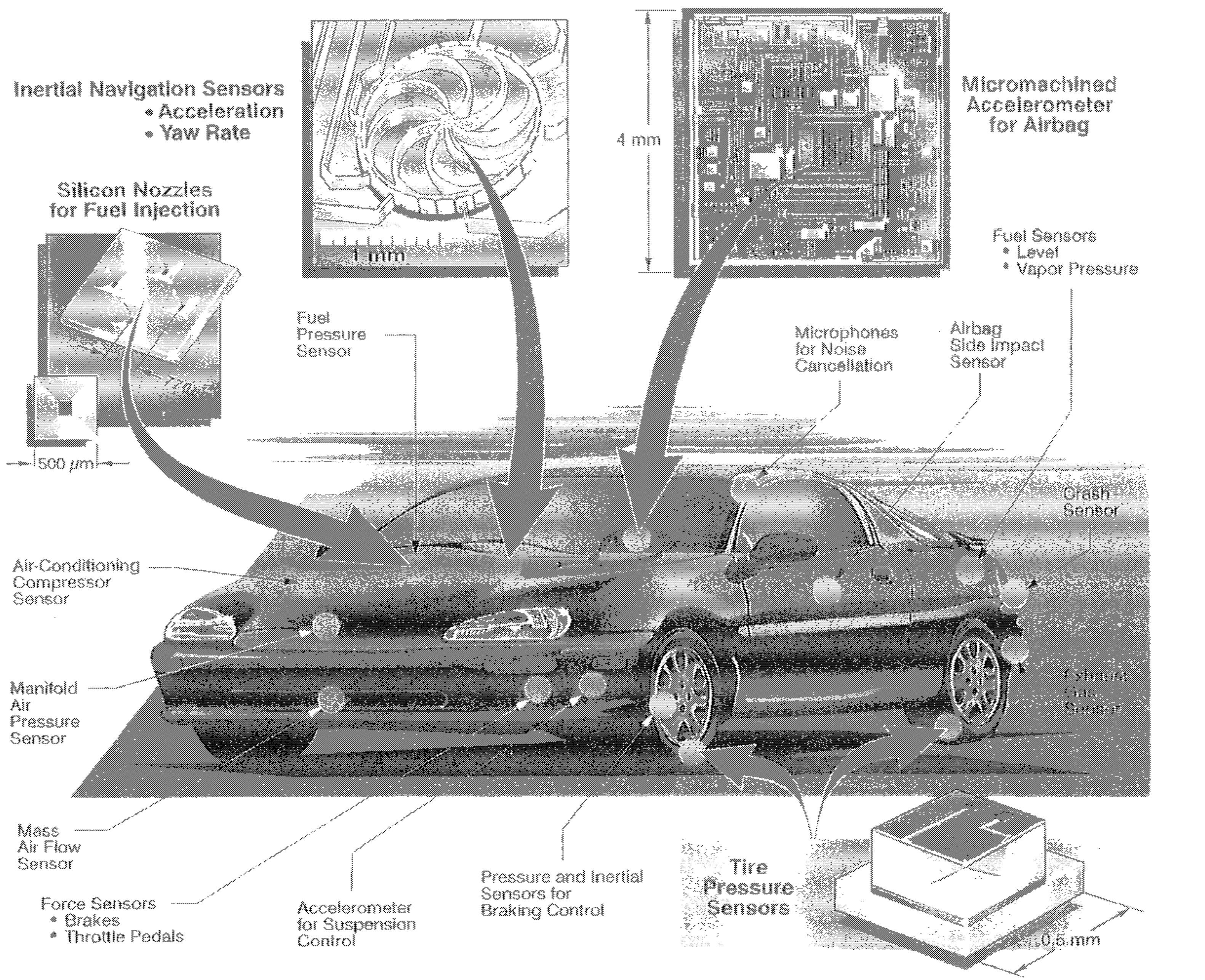

FIGURE 1-8 Concepts for applications of automotive sensors and accelerometers. MEMS could be used to activate suspension systems, control engines and emissions, control vibration, and cancel noise. Source: D. Thomas, Perkin-Elmer Applied Biosystems, based on concepts by G. Kovacs, K. Petersen, and M. Albin.

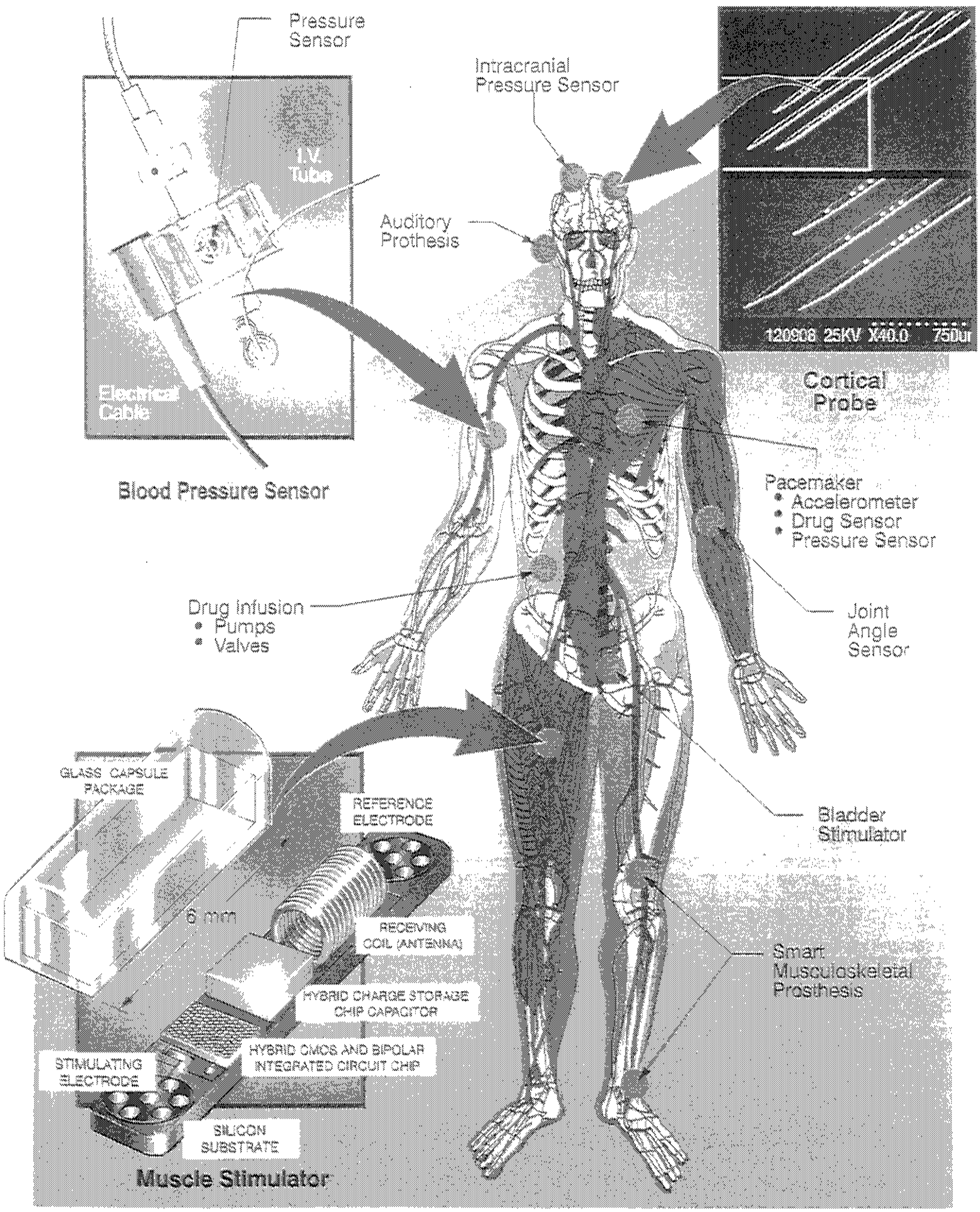

FIGURE 1-9 Potential MEMS to monitor the condition of the body remotely and actuate implanted MEMS devices to release controlled doses of medicine. Source: D. Thomas, Perkin-Elmer Applied Biosystems, based on concepts by G. Kovacs, K. Petersen, and M. Albin.

Packaging takes on special importance for chemical-sensing applications, as does the need for fundamental studies of flow in small channels and of liquid-solid interface effects. These areas still present challenges, but the barriers are surmountable. Indeed, much work is under way to bring the promise of MEMS to fruition in this area.

LONGER-RANGE OPPORTUNITIES

In some instances, MEMS have made the transition from research to commercial products, some with very large markets. Until now, however, MEMS have remained mostly in the *first phase* of product realization, which offers an improvement over what is already on the market. For example, the MEMS accelerometer does not enable the implementation of air-bag safety systems; rather MEMS accelerometers offer cheaper systems and better performance. MEMS technology is now poised to enter a *second phase* of product realization, which is marked by the creation of entirely new markets. As a fully integrated system, a MEMS can provide products that know *where* they are, *what* is occurring around them, and *how* to affect a particular outcome.

Future MEMS applications will not only allow information gathering and communication at a distance, but they will also sense and control environments remotely at low cost. With this combination of capabilities, MEMS will play a key role in large sectors of the economy, including health care, transportation, defense, space, construction, manufacturing, architecture, and communication systems. A few potential examples of the opportunities for MEMS are described below.

Transportation

MEMS can improve the performance and reliability of all vehicles, especially automobiles and airplanes. Sensors and accelerometers could potentially be used in the automotive industry, for example, for active suspension systems, engine and emissions control, vibration control, and noise cancellation (see Figure 1-8). In the aerospace industry, MEMS sensors could be used for detecting flow-instability, avoiding stalls, and monitoring structural integrity, as well as for controlling engines and emissions and canceling vibration and noise.

Biomedical and Health Care

In addition to using MEMS to reduce the high costs associated with diagnostic testing, researchers are investigating using MEMS to sense the condition of the body and actuate implanted reservoirs to release controlled doses of medicines (Figure 1-9). Portable MEMS-based analytical instruments are under development that will enable communication and control with remote locations and permit the exchange of information with remotely located experts.

Information Technology

With microactuated *read-write* heads and instrumented microminiature head housings, researchers predict a tenfold increase in recorded information density in MEMS-engineered microdisk drives. Disk-drive systems with the storage capacity of the current 3.5 inch systems would shrink to approximately the size of a U.S. quarter dollar. MEMS could also make a major impact on the radio-frequency field through the development of integrated switches, high-Q filters, and other integrated components.

Defense

MEMS could substantially improve the performance, safety, and reliability of weapons systems without compromising their shape or weight. The small size of MEMS makes the inclusion of redundant systems feasible, as well as the implementation of fault-tolerant architectures that are modular, rugged, programmable, conventionally interfaced, and relatively insensitive to shock, vibration, and temperature variations. MEMS could also make sophisticated new functions in weapons feasible, such as systems that understand and communicate their condition, enabling the early detection of incipient failure. Other potential functions for MEMS include the detection of tampering.

SUMMARY

The continued evolution of MEMS technology reflects the ongoing ability of scientists and engineers to shrink electronic devices while simultaneously increasing their performance. These advances have had remarkable effects on both technology and society at large. For example, commercial successes that have evolved from MEMS technology include the greater than $1 billion ink-jet printer cartridge market, as well as the smaller but still very sizable markets for products using MEMS for pressure sensors and accelerometers. Evidence of continued development of MEMS technology is apparent in their emerging use in high-resolution displays and chemical sensor arrays. These examples, however, demonstrate the *first phase* of product realization. Longer range opportunities for MEMS application in the *second phase* of product realization include applications in the transportation, health care, information technology, and defense industries. The descriptions in this chapter illustrate a limited number of areas in which substantial MEMS activity was already under way. A broader, frequently updated picture of the MEMS field can found on World Wide Web sites that focus on MEMS (see Appendix A).

2

Integrated Circuit-Based Fabrication Technologies and Materials

A hallmark of the microelectronics industry is the sustained exponential growth in the performance and complexity of ICs over the past four decades. As complexity and speed have increased, the cost of logic functions, memory, and central processing units (CPUs) has dropped dramatically. The IC field has demonstrated an ability to develop new fabrication processes and materials that are both manufacturable and reliable.

The allure of the emerging field of MEMS is that it can exploit the microelectronics fabrication and materials infrastructure to create low-cost, high-performance systems. The goal is to achieve the levels of performance, manufacturability, reliability, and low costs that are normally associated with microelectronic products. This chapter examines the strengths of various IC-based technologies and their uses for MEMS.

STRENGTHS OF THE INTEGRATED CIRCUIT PROCESS

At least eight characteristics of the IC process have led to its phenomenal growth. Examining these characteristics can provide a helpful perspective for MEMS development.

ICs are *batch fabricated* so that a great number of circuits and hundreds of millions of electronic devices can be fabricated simultaneously on the surfaces of many wafers. In terms of first-principle effects, it is no more expensive to build 100 circuits on a wafer than it is to build only one. Because interconnection of the enormous numbers of devices is part of the fabrication process, potentially error-prone assembly steps, as well as connection failures during operation, are avoided. These desirable characteristics of batch fabrication are key to the low costs, manufacturability, and reliability associated with ICs.

In current IC production, a *common set of materials and repeated process steps* can be used to manufacture numerous circuits that may, in turn, be used by many diverse designers. In a typical IC process being used today, materials, basic circuit building blocks, and wiring and design rules are standardized. This *standardization* has led to a fundamental mastery of technologies and engineering for IC production. New products, designs, and extensions of technology continue to leverage the significant knowledge base that has been developed over the past 40 years.

Using the IC planar processes, the *sizes and configurations of microelectronic elements are defined by computer-drawn figures*. By exploiting photolithographic techniques, device features can be controlled at the submicrometer level. This control has led to fantastically high performance coupled with very high device density in many products, such as the computer-on-a-chip.

Computer techniques to aid in IC design have evolved to an extremely sophisticated level. The process, circuit function, device operation, and layout can all be *simulated and designed with computers*. Interaction among diverse groups of designers and users can be conducted through the exchange of software. The maturity of CAD methodologies for integrated circuits has contributed greatly to the success of ICs.

The IC process uses one of the *cleanest and most carefully monitored fabrication environments* of any large-scale production process. Although this environment is costly to implement, it leads directly to process controls that have increased the yield and reliability of products.

The processes used to produce ICs are very carefully controlled with *in-process test structures that are typically made an integral part of the production sequence*. The control of patterning and the degree to which impurities can be repeatably introduced and monitored are typically far more precise than for other manufacturing processes.

Standardized IC production processes are *accessible to users on a contract basis through IC foundries*. This accessibility is very important because maintaining a modern IC production line is very costly (e.g., costs of Intel production facilities are in the billions of dollars). Thus, although large IC producers typically conduct all of the production steps for the ICs they market, smaller industries can design ICs to be produced at foundries that receive only computer layouts to define the products. This production mode has been validated over the years through the MOSIS program, which was sponsored by the Defense Advanced Research Projects Agency (DARPA) and the National Science Foundation (NSF). The MOSIS program has served both industry and academic institutions.

After more than 40 years of development, a *large complement of IC engineers have been trained.* These engineers provide a very important resource that directly contributes to the continued development of ICs. By taking advantage of the freedoms provided by the IC design procedures, engineers have come up with new designs and ideas that have extended the IC process far beyond what was first envisioned.

Clearly, the characteristics of the IC process just described should be applied to the production of MEMS as much as possible. Focusing on ways to leverage the multibillion-dollar investment in the IC infrastructure will be effort well spent.

Many of the processes that have been refined in IC technology to produce electronic devices can be adapted to make the mechanical structures needed in MEMS. These processes include those that support photolithography, plasma etching, wet etching, diffusion, implantation, chemical-vapor deposition, sputtering, and vacuum deposition. The most sophisticated IC production uses very high performance equipment (to control submicron line widths, for example). Such fine dimensional control is not required in typical MEMS applications, which therefore might be able to use earlier generation equipment. Thus, in some cases, MEMS fabrication facilities can make use of older IC processing lines, thereby reducing startup costs (for new industrial ventures) or making it feasible to open MEMS-capable fabrication facilities in government laboratories or universities.

USING EXISTING INTEGRATED CIRCUIT-BASED PROCESSES

This section enumerates several IC-based fabrication processes that have been used to produce MEMS. Opportunities and technical challenges for each fabrication process are highlighted, and recommendations are given to address the technical challenges of IC-based MEMS processing technologies.

Existing IC-based technologies that have been used to produce MEMS are generally described by the terms *bulk micromachining* or *surface micromachining*. In bulk micromachining, the mechanical device is composed of the substrate material (e.g., single-crystal silicon), whereas in surface micromachining, the mechanical device is made from material deposited as part of the fabrication process. In a few cases, this distinction does not apply because sequential steps produce a composite device, but the dominance of either surface or bulk micromachining in the process is usually apparent. Compatible processing with ICs has been demonstrated using either technique, but the complexity of the process, the sizes and possible shapes of the mechanical elements, the sizes of the chips, the minimum sizes of the features, the costs, and the yields are all strongly influenced by the chosen process and the level of system integration in the MEMS.

Bulk Micromachining Processes

Bulk micromachining was first demonstrated decades ago. In its original form, it produced structures by using anisotropic wet etching of the single-crystal substrate. By combining the constraints of directionally dependent and impurity dependent etching with photolithographic patterning, a number of useful three-dimensional configurations (Figure 2-1), notably cantilevers, diaphragms, and orifices, can be produced. The rates of the anisotropic etches are greatly reduced by heavy boron doping, and either this effect or the presence of a pn-junction is often employed to control etch depths. The original bulk-micromachining process is widely used today, especially for the production of pressure sensors. Newer techniques have also been introduced to add features to bulk micromachining.

Two techniques rely on wet-chemical etching or RIE (reactive-ion etching) to form structures from bulk material. Released structures are formed by etching through the bulk material or by undercutting the bottom structures to be released with a selective wet or plasma-etch step and a masking material. Released structures can also be formed using a substrate with two or more layers: the micromachined device is formed from the silicon remaining in the upper layer after the lower (buried) layer is dissolved, releasing the structures selectively.

Other techniques used to micromachine bulk material include scanned, focused-ion-beam or laser ablation to remove materials; masked ion-beam etching or ion milling; and mechanical removal of the unwanted silicon. These technologies are serial rather than batch processes and do not usually provide the economies of scale offered by most IC manufacturing techniques. Serial scanning tools are useful for cross-sectioning or calibrating suspended MEMS, however, by selective material removal or selective material deposition.

A bulk-micromachined accelerometer (Figure 1-4) highlights the characteristics of the wet-chemical etching of single-crystal silicon for MEMS. The process involves lithographic patterning of the device onto a silicon dioxide mask layer. This step is followed by a pattern-transfer step that exposes areas for subsequent wet-chemical etching using potassium hydroxide (KOH) or other suitable wet etch. The KOH etch is anisotropic and faster on different crystallographic planes. The crystal orientation of the surface is normally the plane so the silicon etches much slower in the normal direction than in the direction lateral to the surface. The shape of the finished structure has sloped sidewalls and facets on corners or curved patterns. Etched square patterns become inverted pyramids. The etching times may be minutes or hours.

Two advantages of wet-chemical micromachining are that large structures can be micromachined from silicon in a short time and that the chemical-etch equipment is simple and inexpensive. Disadvantages of wet-chemical processing are

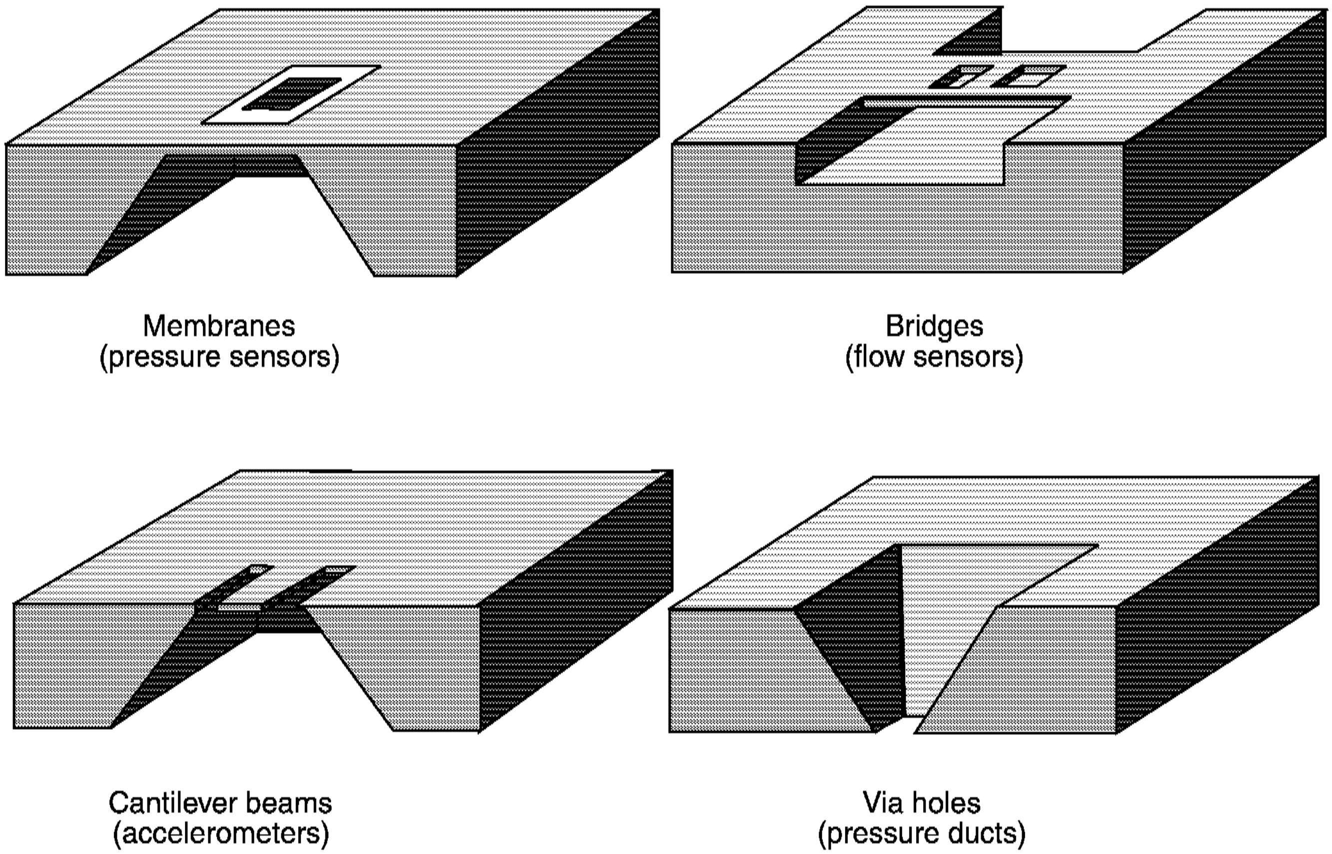

FIGURE 2-1 Three-dimensional configurations that can be produced by combining directionally dependent and impurity dependent etching with photolithographic patterning.

that patterned features must be spaced relatively far apart so that adjacent features do not merge by the lateral etching of the features. Also because of lateral pattern etching, the features on the mask and pattern transfer layer must be biased or reduced (and sometimes even distorted) to achieve the desired feature size and shape at the completion of the etch process. Thus, complex curved patterns and closely spaced structures—closer than a few micrometers—are very difficult to make using wet-chemical etching.

Bulk micromachining process technology is currently undergoing a revolution driven by the incorporation of deep reactive-ion-etching (DRIE) of silicon as a replacement for orientation-dependent (wet) etching. The traditional wet etches limit the range of structures, shapes, and minimum geometries because they rely on the crystallographic orientation of the wafer. DRIE eliminates many of these restrictions, allowing 90-degree sidewall angles (which reduces device size) and randomly shaped linear geometries (Figures 2-2 and 2-3). The DRIE process can also produce structures with high-aspect ratios similar to those produced by LIGA.

DRIE bulk micromachining can be implemented in many ways, from single wafer, diaphragm, or structured devices, to more complex bonded wafer structures. An example of a bonded wafer accelerometer structure is illustrated in Figure 2-2. The bottom wafer can either be patterned by traditional wet etching methods (a) or can have an oxide defined region that will later be removed by sacrificial etching. A second silicon wafer is bonded to the bottom wafer (b, c) creating either an enclosed cavity or an enclosed oxide region. Lithographic patterning and DRIE are performed on the surface of the top wafer, defining the structural components on the accelerometer (d, e). If the buried oxide method is used, the oxide is then removed by sacrificial etching. Using DRIE in this manner allows the development of non-orthogonal, complex shapes (Figure 2-3). This method can also be used with

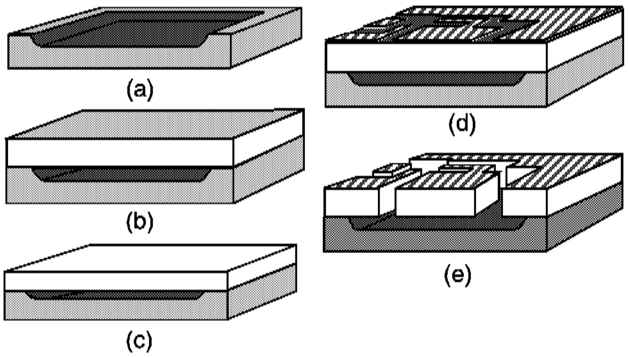

FIGURE 2-2 Generalized process flow for silicon fusion bonding and deep reactive-ion etching (DRIE). (a) A cavity is etched in the bottom wafer. (b) A second wafer is fusion bonded onto the bottom wafer, forming buried cavities. Wafer bonding is also possible with an intermediate oxide to provide electrical isolation. (c) The top wafer is polished down to the desired final thickness. This can also be done by various types of electrochemical etching steps. (d) The metallization and patterning is done along with the DRIE masking and patterning. (e) The DRIE etch through the top wafer into the buried cavity releases the microstructures. Source: Klaassen et al., 1995.

other devices and wafer stacks to produce an entirely new class of bulk micromachined silicon devices.

Controlling the etching of films and bulk silicon needs further study. Since the fabrication of three-dimensional structures is almost intrinsic in the world of integrated MEMS, etching in a controlled fashion and tailoring the isotropic or anisotropic etch-rates of various materials is desirable. Methods and processes to integrate electrically and/or thermally isolated segments of the suspended micro-structures are also important for making MEMS.

Bulk Micromachining for MEMS with Electronics

Bulk micromachining with integrated electronics makes use of the mechanical, electronic, and thermal-oxidation (silicon dioxide) properties of single-crystal silicon. Additional advantages of bulk micromachining with electronics include the ability to fabricate suspended, very-high-aspect-ratio (100:1) structures over a large area and the partitioning of the major portion of the electronics off-chip.

One approach to the bulk micromachining of devices with electronics is to partition the silicon chip area to separate the MEMS from the electronics. The electronics area is fabricated first using standard multiple mask-level silicon processing, reserving and protecting selected areas for the MEMS. Subsequent processing sequences are then used to fabricate the MEMS (Figure 2-3). The bulk micromachining steps are usually used to protect the completed electronics during the

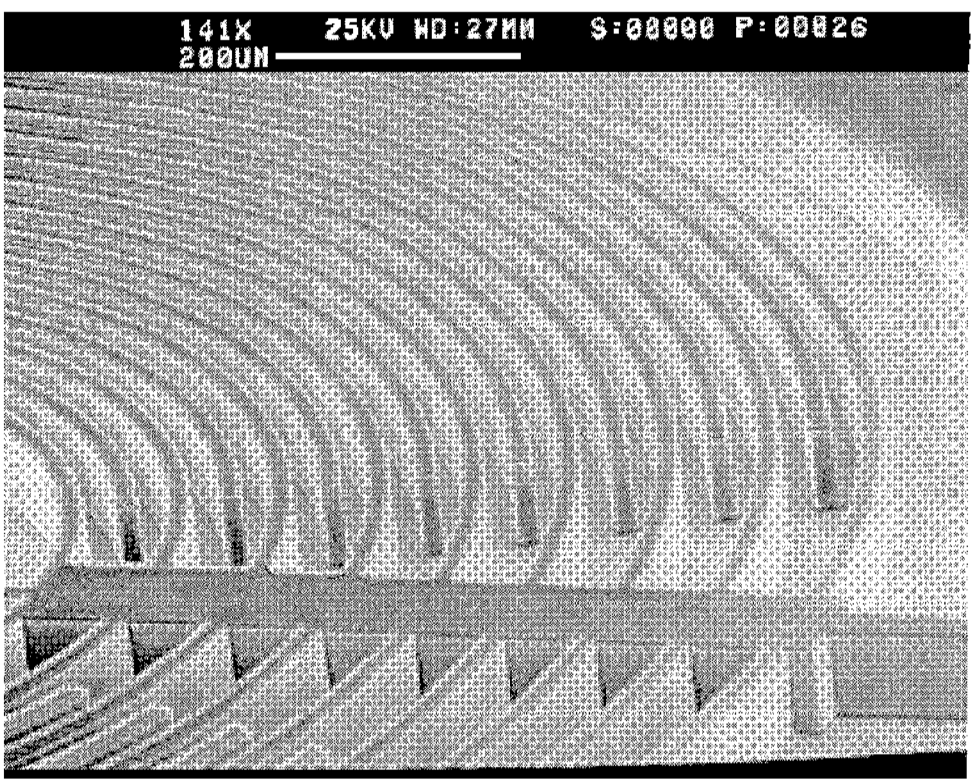

FIGURE 2-3 Torsional MEMS structure made possible by DRIE bulk micromachining processes. Source: NovaSensor.

wet-chemical etching or RIE of selected areas, as described in the previous section. Ionic contamination, surface charging, and elevated temperature cycling can affect the operation and ultimate stability of the electronic devices. RIE-based processes, which do not require high temperatures and do not expose the wafers to ionic contamination, allow the fabrication of single-crystal silicon structures with structure spacings limited only by the lithography and pattern-transfer processes.

Although bulk micromachining techniques allow for transistors and interconnect elements to be integrated on suspended or isolated silicon structures, it is generally only possible to produce the electronics before performing bulk etching for mechanical structures. Key challenges for post-transistor micromachining include protection of the electronics from wet-chemical attack, planarization of the wafer surface before initiating the micromachining, and the inclusion of nonstandard MEMS processes and materials. The addition of materials that are not IC-compatible usually requires that the MEMS be fabricated after completion of the IC processing.

Another approach is to integrate the electronic and micromachining process steps. The advantage of this approach is that electronic devices can be integrated on complex suspended and moving structures to provide local power, amplification, impedance matching, and switching. In addition, integrated electronics with MEMS processing can minimize the complexity of the on-chip electronics for specific applications and may make it possible to partition the major electronic functions off-chip, allowing the use of standard electronic chips or application specific ICs (ASICS) for signal processing and control.

Thin bulk-micromachined, single-crystal silicon structures with integrated electronics can also be made using the "dissolved-wafer process" (Najafi and Wise, 1986). An example of a device fabricated with this process is a multichannel neural probe with integrated electronics (Figure 2-4). In this process a boron etch-stop is used to terminate a back-side etch below the micromachined structures and electronics integrated on the wafer top side.

The challenges of bulk micromachining with electronics include the need for DRIE and/or wet-chemical etching of silicon; the need to protect prefabricated microelectronics from subsequent micromachining steps; and the possible need to planarize the wafer surface via thick photoresist steps and/or chemical-mechanical polishing. The recent introduction of high etch-rate (> 2μm/min) inductively coupled plasma (ICP) tools has generated renewed interest in bulk micromachining with integrated electronics. The introduction of high etch-rate ICP tools in semiconductor laboratories makes the cost structure of RIE etching less prohibitive as an alternative to surface micromachining.

The challenges of DRIE processes include: controlling the isotropic undercut etch; designing the microstructures so that they can be thermally isolated without distortion; increasing the etch rate above 3μm/min and/or increasing the production throughput using multiple-wafer DRIE tools; developing conformal deposition processes that deposit uniform layers of ceramics and metals on the sidewalls of the high-aspect-ration processes; developing low-temperature deposition processes compatible with deposition on completed ICs; and developing multiple level bulk micromachining processes.

FIGURE 2-4 Multichannel neural probe with integrated electronics fabricated by the dissolved-wafer process. Source: Najafi and Wise, 1986.

Surface Micromachining Processes

Surface micromachining makes use of traditional microelectronics fabrication techniques to create mechanical systems with micron-sized features. In contrast to bulk micromachining, which forms structures by etching into the bulk of the wafer, the hallmark of surface micromachining is that mechanical features are etched into thin films that have been deposited on the surface of silicon wafers. The surface-micromachining method can use any of several materials as the mechanical layer with variations serving as the sacrificial layer. Most often, polycrystalline silicon is used for the mechanical layer and silicon dioxide is used for the sacrificial layer because these materials are the most easily adapted from the materials available in the IC field and their fabrication techniques permit the simultaneous fabrication of thousands or tens of thousands of mechanical structures across the surface of the wafer.

A typical polysilicon-based process begins by depositing a thin film (~0.5 to 2.0 µm) of a sacrificial material onto the surface of the wafer. A common sacrificial material is a chemically vapor-deposited (CVD) oxide. Traditional photolithography and dry-etch processes are then used to cut holes at selected sites through the sacrificial layer to the silicon surface. These holes serve as the anchor sites for the structural material to contact the underlying wafer. The thin film of structural material is then deposited, patterned, and etched to form the micromechanical structures. The fabrication sequence is completed with the immersion of the wafer in hydrofluoric acid, the etch rate of which is very different for polycrystalline silicon than for silicon dioxide. This highly selective release-etch removes the silicon dioxide and leaves the polycrystalline silicon structures suspended above the wafer surface everywhere except where the anchor cuts were made.

Surface-micromachining techniques have been used to create a variety of sensors and actuators, including accelerometers, gyros, pressure sensors, combustible-gas sensors, and a variety of resonant structures. Many of these devices are now in commercial applications, especially accelerometers. Devices fabricated using surface micromachining use similar process-control and batch-fabrication techniques to those developed for the IC-industry. Using these well established techniques enables the batch fabrication of low-cost, high-performance MEMS. Because the nominal thickness of the polycrystalline silicon layer is 2 µm, however, the out-of-plane stiffness usually limits the suspension span of the microstructures and devices to a few hundred micrometers. The structure release and drying steps also limit the maximum size of the suspended microstructures.

An important challenge in surface-micromachining fabrication comes at the end of the fabrication sequence, however, during the final rinsing and drying of the wafers. After the sacrificial material has been removed and during the final drying process, a meniscus forms between the bottom of a suspended mechanical structure and the surface of the wafer. As the water dries, the meniscus pulls the suspended mechanical structures toward the surface, and the structures become stuck together. A similar meniscus can form between adjacent mechanical structures, causing them to stick together. This phenomenon is known as stiction.

A low-cost manufacturable technology requires that the problem of stiction be overcome. Several techniques have been developed to circumvent the problem. First, design techniques have been used to minimize stiction by limiting the area of contact between suspended structures and the substrate. One way to accomplish this is to etch regularly spaced *dimple cuts* into the sacrificial layer before the deposition of the structural material. Unlike the anchor cut, the dimple cut does not perforate the entire sacrificial oxide layer. When the structural material is then deposited onto the sacrificial layer, the material conforms to the dimples in the sacrificial layer, and small bumps are formed along the bottom of the structural material. These bumps limit the contact area between the suspended structures and the substrate and mitigate the stiction problem.

Several promising process techniques have also been developed for reducing or eliminating stiction. For example, the meniscus problem can be completely eliminated by utilizing a supercritical CO_2 drying technique in which the sacrificial release-etchant is displaced with water and then with methanol. The wafers are then placed in a pressure chamber where liquid CO_2 is introduced to displace the methanol. The temperature is raised to transform the liquid CO_2 to a supercritical fluid, after which the pressure is dropped, returning the supercritical fluid to a gaseous state. Thus the liquid-to-gas transition interface that creates the meniscus problem is completely avoided. This CO_2 technique has been used to release structures that are millimeters in size and has enabled the high-yield manufacture of complex surface-micromachined MEMS. Supercritical CO_2 drying is a standard process in the food-processing industry and is an excellent example of how existing industrial manufacturing techniques can be adopted by the MEMS industry.

A related technique to avoid the formation of a meniscus is the freeze-sublimation technique in which the release etchant is displaced by water and then by an organic solvent with a high freezing temperature. The wafer with solvent is cooled until the solvent is frozen. The pressure is then dropped to vacuum levels, and the frozen solvent sublimes. This technique is analogous to the common food-processing technique of freeze drying. Another way to avoid stiction is to make the surface hydrophobic by coating it with ammonium ions.

The techniques described above avoid stiction during drying, but stiction can still be a problem during the operation of actuated MEMS. If shock, electrostatic discharge, or some other stimulus causes individual MEMS components to touch either each other or the substrate, they may become stuck. In these cases, surface treatments are needed to change the energy state, or "stickiness," of the surfaces. Promising results from treatments with amoniafloride have been demonstrated, and work with several self-assembling monolayers have shown promising results at the early research stage in reducing both stiction and friction (Houston, Maboudian, and Howe, 1995). The development of manufacturable low-stiction surface modifications for the commonly used surface micromachining materials is a major area of investigation.

Surface Micromachining to Produce Multilevel MEMS

Dramatic increases in mechanical complexity and functionality can be achieved with surface micromachining technologies that incorporate two or more levels of polysilicon. Continued extension of the technology enables the fabrication of mechanically complex systems, including motors, tools, and the interconnections to couple them. Fabricating micromachines with three or more levels of structural polysilicon requires more than a logical extension of simpler technologies, however. Almost all microelectronic fabrication tools were designed to work with near-planar surfaces. As micromachines are formed on the surface of the wafer, nonplanarity and significant nonplanar topography begin to develop. Each additional level of polysilicon complicates the topography problem. The sacrificial layer that is placed on top of a structural level of polysilicon conforms to the shape of that layer. When another layer of polysilicon is deposited, it is not flat, so the structural details of the first level are, in effect, imprinted on the upper level. This problem is compounded with each level of polysilicon. The problem can result in the presence of untenable stringers, alignment difficulties, and unintended structures that can interfere with the proper operation of the micromachine. Topography problems complicate the development of surface-micromachining technologies that have three or more levels of polysilicon.

The established IC-fabrication technique of chemical-mechanical polishing (CMP) may be able to overcome topography problems in multilevel polysilicon technologies. Using CMP, wafers are polished flat after each sacrificial-oxide deposition, which results in perfect planarity of each structural level and eliminates the stringer and mechanical parasitic problems. MEMS have been built with five levels of polysilicon using the CMP technique.

Surface micromachining has matured sufficiently to give rise to foundry services. MCNC, under DARPA sponsorship, offers a very inexpensive foundry service for surface micromachining. The technology offers two structural levels of polysilicon and an additional level of polycrystalline silicon for electrical interconnection. A broad variety of researchers have made use of this service to create both simple and complex structured MEMS.

Surface-micromachining technologies can also be used on material systems other than structural polysilicon and sacrificial layers of silicon dioxide. For example, TI uses a photoresist as the sacrificial layer and aluminum as the structural material in their DMD (Hornbeck, 1995). There are several important considerations in choosing combinations of materials for surface micromachining, however. First, to create fully released structures, sacrificial and structural materials must be chosen that react to some highly selective etchant. Second, the ability to deposit the structural material in a low-stress state or to achieve a low-stress state through a thermal anneal is critical to prevent curling of the mechanical parts when they are released. If high-temperature anneals for stress reduction are needed, the underlying sacrificial layers must be able to withstand the treatments. Another consideration is the advantages of using well known and accepted microelectronic materials.

CLASSIFYING INTEGRATED CIRCUIT-BASED TECHNOLOGIES

The objective of this section is to classify the IC-based technologies that have been or might be useful for the manufacture of MEMS. The classification can be of value in assessing the cost/benefit ratios of a proposed MEMS process and in stimulating thought about new directions for MEMS.

From the IC experience, it is clear that innovation in either materials or procedures exacts a cost, and every innovation must be evaluated in terms of a cost/benefit analysis. The degrees of innovation are not readily quantifiable; they are defined on the basis of MEMS experience and an understanding of the steps in the IC process. Fuzzy definitions are regrettable but probably unavoidable. For example, from one perspective, the polysilicon used for substrate micromachining differs substantially (in terms of its deposition procedures, dimensions, and physical properties) from the polysilicon made for electronics use in ICs and could be classified as a *new* material.[1] This distinction will not be made in the following sections. Polysilicon will be treated as an *old* material.

MEMS production processes will be characterized in the following sections in terms of two sets of variables: (1) the materials being processed and (2) the processing steps and equipment (tools). Innovation in either set will generally incur "startup costs" in terms of money, time delays, and/or extra work for qualification purposes. As an example, polysilicon surface micromachining, described earlier in this chapter, is carried out using materials that are well known in IC manufacture (*old* materials) and with IC process steps that are also well known (*old* tools). If the surface micromachining process were to be complicated by moving to more than three layers of structural polysilicon, a CMP step would probably have to be added, which can be considered a *new* tool and would add a level of complication to the process.

MEMS with Old Materials and Old Tools

MEMS that use only those IC processes now in use for integrated microelectronics are most acceptable to the existing manufacturing capabilities. Some MEMS have been successfully made this way (usually with a few added post-IC-process steps). The design space is severely limited,

[1] Structural polysilicon is usually a thicker film of polysilicon, the internal stress and internal stress gradients of which are engineered. Lower-temperature processing and engineered anneal-cycles are required for the mechanical elements to have the desired properties.

however, and the designer must account for relatively uncontrolled mechanical properties in the structures.

Many years of experience in the production of silicon diaphragm pressure sensors clearly qualifies their production processes as old tools. However, when they were first introduced in the 1960s, anisotropic wet-etching and etch-stopping with highly doped boron layers would have been *new* tools. The subsequent development of nozzles for silicon ink-jets using anisotropic etching was aided by experience with the diaphragm pressure sensor. As this example shows, the number of tools in this first classification of MEMS processes grows as mastery of once-new materials and technologies grows.

Cleverness is the important parameter that can lead to advances in this category. A clever MEMS engineer should reconsider older processes that are only occasionally (or no longer) used and capitalize on established know-how if resurrecting them should prove worthwhile. Many of the MEMS technologies in this category are product-specific, however. For example, two of the most advanced MEMS products are TI's DMD and Analog Device's integrated accelerometer. Both products leverage existing microelectronics fabrication techniques but utilize different structural and sacrificial materials. Consequently, solving manufacturing problems for one would not necessarily solve problems for the other.

MEMS with Old Materials and New Tools

New tools in the MEMS area have traditionally been qualified through their use in specialized areas—often in a selected region of the IC world. An example that appears to have many MEMS applications is DRIE, a process that was developed to open a third dimension in IC semiconductor-memory applications. As described earlier in this chapter, bulk-silicon microstructures have historically been produced through the use of wet-chemical etchants. Although wet-etching techniques are well established, they have a number of drawbacks, including the inability to achieve vertical sidewalls and non-orthogonal linear geometries in <100> silicon and the reaction of wet chemicals with films on the wafer surface. A capability to produce high-aspect-ratio, vertical-sidewall features in silicon is being provided using DRIE techniques and several recent commercial systems. Significant reductions in device area can be realized by changing the etch sidewall angle from 54.7 degrees to ~90 degrees for devices that use back-side etching to produce or release front-side structures. This technology has applications in all areas of traditional bulk micromachining, such as pressure sensors, fluidic microstructures, and accelerometers. An example of an inventive use of DRIE is for the process called HEXSIL (combining HEXagonal honeycomb geometries for making rigid structures with thin films and SILicon). HEXSIL (discussed further in Chapter 3) combines surface micromachining with DRIE trenches in silicon (Keller and Ferrari, 1994).

Although DRIE has provided new options and opportunities, it still presents a number of challenges. First, although at present DRIE provides the capability of etching a few hundreds of microns into (or through) a silicon wafer, the silicon etch-rate is dependent upon the width of the exposed silicon feature, which leads to varying etch depths as a function of feature size (Figure 2-5). Work needs to continue either to eliminate the etch-rate dependency or to develop design and processing rules to correct for it. DRIE would then be applicable to the broadest class of structures. Second, although the silicon etch-rate has increased by orders of magnitude over the rate for earlier generations of silicon RIE machines, the current rate is only *microns per minute*. This rate might be tolerable if the equipment were capable of batch-wafer processing, but current and near-term equipment is suitable only for single-wafer processing. To use DRIE in a process that requires more than 100 microns of etching would necessitate installing systems with multiple etch-chambers to maintain a production schedule. Third, the DRIE process may be well suited for silicon materials, but it is generally not appropriate at this time for other materials (e.g., dielectrics, metals, or ceramics). The importance of extending DRIE to nonsilicon materials is becoming increasingly apparent, however, as microfluidic applications for MEMS grow in importance. Configured fluid channels and devices in glass, plastics, ceramics, and metals warrant developing DRIE methods for processing them.

MEMS with New Materials and Old Tools

The category of new materials and old tools is very important for emerging technologies because it does not require significant capital investment. Ideally new materials would

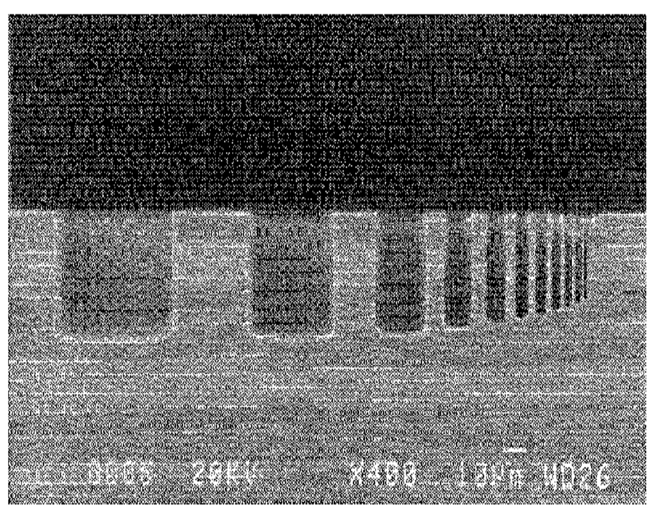

FIGURE 2-5 Deep reactive-ion etching (DRIE) depth as a function of feature width. Features shown are 2 to 50 microns wide. Source: MCNC MEMS Technology Applications Center.

be introduced as thin films and could be used with processes and equipment familiar to the IC world (e.g., low-pressure chemical-vapor deposition [LPCVD] or, less favorably, sputtering). Similarly, CVD processes in standard CVD equipment could be used with temperature and flow changes to make familiar materials with new properties. Low-stress silicon nitride is a material that could fall into this classification. It is generally deposited in the same LPCVD tubes that historically have produced stoichiometric silicon nitride but with significantly different gas flows and pressures. Efforts are also under way to incorporate materials with useful properties for sensing and actuation, such as ferroelectrics, piezoelectrics, and magnetic films, into MEMS processes (see Chapter 3).

The selective deposition of materials on patterned substrates is common in ICs and will increase as new materials are introduced. The selective deposition techniques for silicon and metals (e.g., tungsten) used in IC processes could find their way into MEMS processing over time. The ways, means, and materials suitable for this whole family of techniques require significantly more fundamental research, however.

MEMS with New Materials and New Tools

The combination of new materials and new tools presents formidable challenges, and progress will probably be slowest in this category. This should not, however, rule out the consideration of this class of MEMS research, but the benefits should be compelling (see Chapter 3). The "newness" of either materials or tools can vary considerably because some materials and tools previously used for special purposes may provide sufficient basic knowledge for them to be transferred easily to the MEMS area. For example, electroplated magnetic materials and processes are familiar from their use in the magnetic memory storage area. If the manufacturing issues specific to micromechanical materials can be successfully addressed, these materials and tool sets may move from being the *most difficult* to the *least difficult* to incorporate. Nevertheless, the application of electroplating will require improved facilities and extensive characterization before the full potential of this technique can be realized.

SUMMARY

The enthusiasm for and promise of MEMS has, to a large extent, arisen from the demonstrated ability to produce three-dimensional fixed or moving mechanical structures using lithography-based processing techniques derived from the established IC field. Conventional IC materials can be used innovatively in MEMS, and much of the needed MEMS-specific hardware can still be leveraged from IC-technology. These MEMS developments are most likely to be accepted in traditional IC fabrication facilities and are, therefore, most likely to succeed commercially.

There are many opportunities for creative work in MEMS based on what is already known about IC processing, particularly in re-evaluating the range of knowledge compiled during the history of IC development. MEMS products that rely on conventional IC tools, materials, processes, and fabrication techniques have the highest probability of achieving the same manufacturability, performance, low cost, and high reliability as in the production of modern VLSI circuits.

At the heart of MEMS development is the ability to construct extremely small mechanical devices, preferably using batch processing. Wet etching has historically dominated the MEMS field because (1) three-dimensional structures can be micromachined from substrate silicon and (2) chemical-etch equipment is well established, simple, and inexpensive. The disadvantages of wet-chemical processing are its inability to achieve vertical sidewalls and non-orthogonal linear geometries in <100> silicon and its reaction with films on the wafer surface. Although dry etching is a mainstay of IC processing and gas-phase "dry" etching techniques are currently being investigated for MEMS production, the film thicknesses or substrate-etch depths for MEMS are often significantly greater than for IC fabrication. Therefore, MEMS etching will typically present additional challenges. If only IC-based techniques are used, it will limit the number of applications that can be pursued. As will be seen in the next chapter, flexibility may open broad new areas for MEMS, although problems with manufacturability and reliability should be anticipated in the early stages.

Conclusion. The expertise and advanced state of the current microelectronics industry provides an enormous advantage for the development of MEMS. Leveraging and extending existing IC tools, materials, processes, and fabrication techniques are excellent strategies for producing MEMS with comparable levels of manufacturability, performance, cost, and reliability to those of modern VLSI circuits. Because controlled etching is so important to the fabrication of three-dimensional structures and the progress of MEMS, improving etching methods, including those that tailor isotropic or anisotropic etch-rates of various materials, will be important.

Recommendation. Efforts to identify solutions to the challenges of producing MEMS should capitalize on relatively well understood and well documented IC materials and processes. Solutions may be found in current IC practices but may also result from creatively re-establishing older IC technologies.

Recommendation. Further research and development should be undertaken to improve etches, etching, and etching controls for MEMS. This work should take into account the realities and limitations of manufacturing process equipment.

3

New Materials and Processes

The previous chapter discussed the application of conventional IC tools, materials, processes, and fabrication techniques to MEMS. This chapter focuses on the rationale and requirements for the introduction of new materials and processes that can extend the capabilities and applications of MEMS *and* that are reasonably compatible with IC-based, batch-fabrication processes. The chapter begins by considering the motivations for introducing new materials and processes. Overviews are then presented of the materials and processes required to produce high-aspect-ratio structures, enhanced-forced microactuation, improved environmental resistance, enhanced surfaces, and improved power supplies.

MOTIVATIONS FOR NEW TECHNOLOGIES

At least five factors motivate the development of MEMS technologies beyond the ones that rely on conventional IC tools and materials. First, some IC-based MEMS are not adequate in applications that require forces commensurate to those in the macroworld. The principal techniques for applying force in IC-based MEMS rely on electrostatic or thermal-expansion prime movers, which produce relatively small forces and limited interaction lengths. Materials other than those available in the typical silicon IC complement will have to be integrated into MEMS to make use of physical prime movers that are potentially capable of delivering higher forces or greater interaction lengths.

The second factor favoring the use of nonconventional IC techniques is the need for high-aspect-ratio structures. In the case of surface micromachining, for example, typical mechanical structures are produced with vertical dimensions limited to a few micrometers. Although a process has been developed to produce "pop-up" elements for applications such as photonic devices (Pister et al., 1992), folded-out polysilicon structures are not suitable for all high-aspect-ratio applications.

The third factor is the need for materials that can operate in severe environments. MEMS applications for chemical analysis, fluid control, and other purposes have been clearly identified in the automotive, electrical, defense, and nuclear industries. These applications, however, demand operation in high-temperature, corrosive environments (e.g., car engines, auto tires, nuclear reactors, chemical process-control facilities, or ordnance).

The fourth factor is the importance of surface effects in many MEMS devices. For example, in chemical- and biochemical-sensor applications, there must be very limited or no interaction between an analyte and the exposed contact surfaces. Methods for modifying and coating the surfaces of exposed devices in MEMS are required to prevent interactions. Solid-solid interface sticking (stiction) might also be mitigated by new materials and processes.

The fifth factor is enlarging the design space for MEMS. This concept is controversial within the MEMS community and has been the subject of considerable debate, which usually centers on the "good versus evil" of standardized processes. Proponents of standardization claim that it is essential for the growth of the industry because it provides a stable, repeatable technology base that can be supported by design rules, distributed CAD support, and the economic yield from many different products. Years of experience in the IC industry have indicated that there is no such thing as a small change in an IC-fabrication process. Changes invariably introduce unforeseen problems. Thus, if new materials or processes are added to a conventional IC process to support MEMS production, they should be added at the back end, preferably off line, in a dedicated process area.

Opponents of standardization are concerned that it will stifle growth while the field is still very young and may exclude some potentially important developments. A similar controversy arose during the early years of IC development, and relative standardization of processes and materials occurred only after more than a decade of commercial production. The IC experience constitutes a prehistory for MEMS, but its consequences in terms of infrastructure provide a strong influence that tends to inhibit the introduction of new materials and processes unless they are shown to be absolutely necessary.

MATERIALS AND PROCESSES FOR HIGH-ASPECT-RATIO STRUCTURES

A serious challenge facing the development and application of MEMS is the production of parts with the structured dimensionality to interface with and affect the macroworld.

This section focuses on two processes that can produce high-aspect ratio (> 100:1), batch-fabricated components that can be integrated with IC-based wafer processing: HEXSIL and LIGA (Lithographie, Galvanoformung, Abformung).

HEXSIL

The HEXSIL method of producing high-aspect-ratio parts (mentioned in the taxonomy section of Chapter 2) involves a combination of DRIE and surface-micromachining techniques. HEXSIL combines HEXagonal honeycomb geometries for making rigid structures with thin films and SILicon for surface micromachining and CMOS electronics. The trenches serve as reusable molds that can be sequentially filled with polysilicon and sacrificial layers of oxide. After patterning and the removal of sacrificial layers, structural members with large lateral dimensions (ranging up to centimeters) can be formed from arrays of polysilicon honeycombs. Thus, through the HEXSIL process, batch processing of thin-film layers can be used to produce elements that form a transition between the millimeter and micrometer worlds.

An example of HEXSIL is a pair of tweezers that can pick up particles ranging roughly from 1 to 25 μm and place them on platforms (also made of HEXSIL) under operator control (Figure 3-1; Keller and Howe, 1997). This basic process has also been combined with nickel plating to produce highly conducting regions on the HEXSIL plates for contacts and conducting patterns. Thermal expansion of resistively heated HEXSIL regions has been used to actuate HEXSIL structures, such as the tweezers. Using interconnected levers, the very tiny expansion in polysilicon beams can be multiplied to produce multiple millimeters of motion (Keller and Howe, 1995).

The HEXSIL process is an interesting example of the way high-cost machines and processes (e.g., DRIE) can support a major leap forward in MEMS. The development costs for trench etchers were paid by IC producers who saw ways to increase the density of semiconductor-memory arrays by adding a third dimension on the chip. For MEMS, DRIE etchers promise nearer-term, silicon-compatible processing of high-aspect-ratio structures. As this promise becomes a reality, MEMS-specific DRIE machines can be expected to evolve. By the same reasoning, fine-structured, nonplanar metal-film plating apparatus and techniques for reliable deep-trench film coating and etching will also be mastered. Because HEXSIL currently uses IC-based technologies, compatibility with these technologies is not an issue. An important area of research required to make HEXSIL a designable and versatile MEMS process, however, is the establishment of the basic mechanical properties (e.g., internal stress, Young's modulus, fatigue strength) of polysilicon so that it can be qualified for new applications.

LIGA

Small, precision-metal components have historically been produced by serial methods, such as computer numerical controlled (CNC) milling or micro-electron discharge machining (micro-EDM). Although serial methods are capable of producing high-precision parts in a variety of metals, they can result in high per-piece costs or part-to-part variations. To drive down the cost of high-precision parts to a level supportable by general systems use, batch-fabrication methods need to be developed.

LIGA (Becker et al., 1986) was developed at the German nuclear research center, the Kernforschungszentrum Karlsruhe, for the production of high-precision, high-aspect-ratio parts in a batch-processing environment. LIGA utilizes x-ray exposure of a resist film, typically polymethylmethacrylate (PMMA), followed by electroplating into the template produced by the exposure to yield a primary metal part. This metal part can be either the final device or, if multiple plastic or metal copies are desired, the master for an injection mold. Figure 3-2 illustrates a basic LIGA process. Figure 3-3 shows metal and plastic parts produced using LIGA.

The LIGA method generally uses nickel or permalloy (NiFe) as the electrodeposited material. Subsequent injection molding usually uses plastics. Multilevel LIGA enables fabrication of components from more than one material or material type for bimorphic applications or friction and wear reduction.

Using multilevel exposure techniques in LIGA processing, which was demonstrated recently (Guckel et al., 1996b), provides for the formation of complex structures, the integration of multiple material layers, and some degree of batch assembly. Multilevel LIGA has a number of added processing requirements, including planarization of the sequentially electroplated layers, adhesion of PMMA to the planarized levels, alignment of the layers, and electroplating of multiple layers.

Compatibility and Manufacturing Constraints of LIGA

The compatibility of LIGA and silicon processing (IC and MEMS) was demonstrated by Guckel et al. (1989), who produced photodiodes in the silicon substrate as part of a motor-position sensing system, and by the HI-MEMS Alliance in the development of a hydrostat that directly integrates LIGA with bulk micromachining (Egert and Felde, 1995). Researchers have successfully demonstrated the utility of LIGA for the production of prototype metal and plastic precision parts, but the transition of LIGA into manufacturing-level processes has been slow. A number of issues and challenges still face LIGA before it can be accepted and integrated into a manufacturing environment. Although some

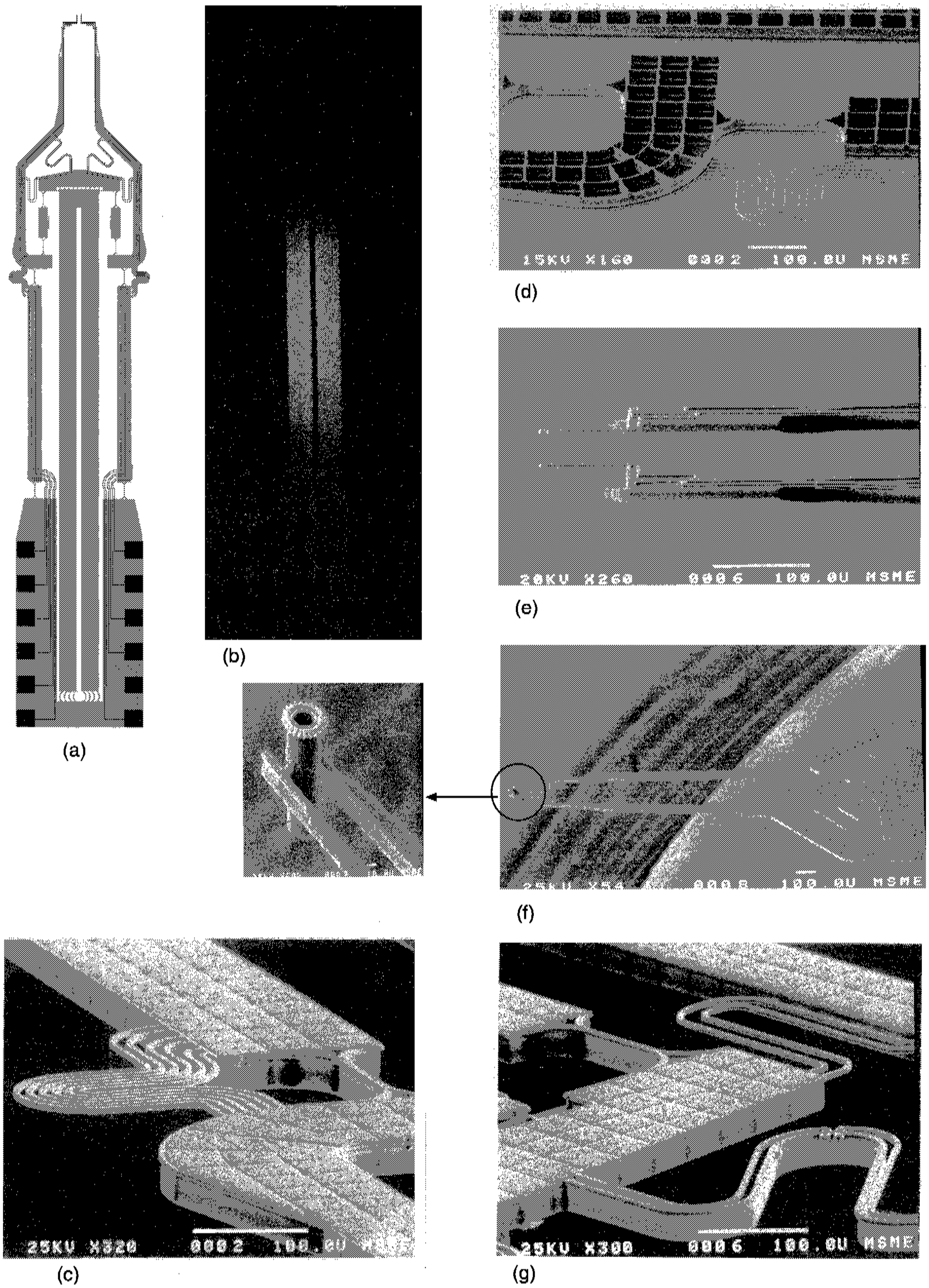

FIGURE 3-1 Photomicrographs of HEXSIL tweezers: (a) HEXSIL tweezers design; (b) center of actuator heated to incandescence; (c) surface polyflex cable for interconnects between rotating rigid HEXSIL beams; (d) bottom view of 45 μm high honeycomb structure of rigid beams; (e) compliant surface polysilicon tips built on HEXSIL foundation; (f) transition from micro- to milli-scale beams provides mechanical interface; (g) semicircular beam with full Wheatstone bridge for position sensing. Source: Keller and Howe, 1997.

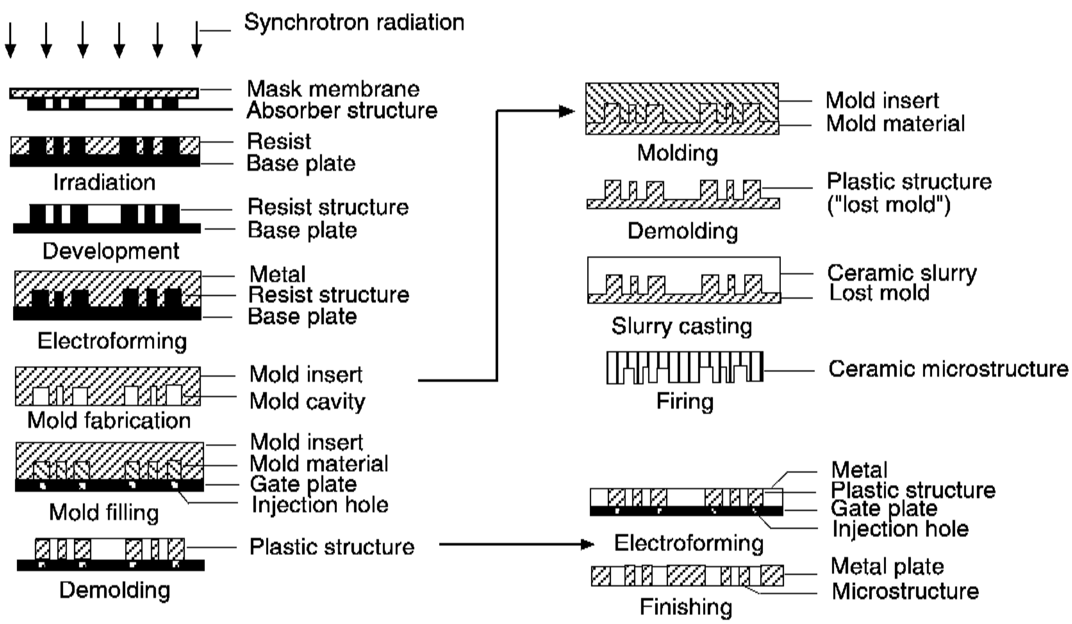

FIGURE 3-2 Schematic illustration of the steps involved in the basic LIGA process. Source: Ehrfeld and Lehr, 1995.

commercialization drivers are being addressed both in the United States (the HI-MEMS Alliance [MCNC] and MEMSTek) and in Germany (Microparts), the adaptation of LIGA into a high-volume manufacturing environment appears to be years away.

Using LIGA in the production of large quantities of high-precision parts is hampered by several throughput constraints. Although all the process steps involved in LIGA are batch- or wafer-level procedures, limitations persist in the following areas: applying the PMMA onto the wafer, the exposure of large numbers of wafers (if replication is not being used), electroplating and "finishing" the primary templates, and using methods like injection molding, hot embossing, and casting for mass replication. There are two major approaches

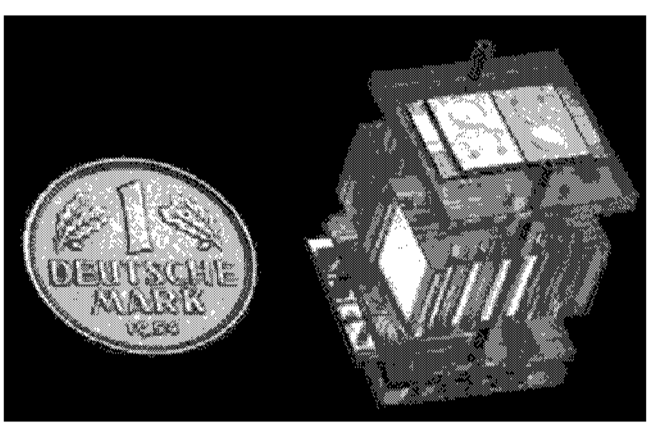

FIGURE 3-3 Metal and plastic parts produced using LIGA. Source: Forschungszentrum Karlsruhe GmbH, Germany.

for improving throughput for LIGA. Most activity in the United States is focused on improving the exposure throughput to allow large volumes of primary template wafers to be produced and eliminate the need for replication. In Germany, the use of replication techniques has been heavily pursued. One reason for the two approaches is the availability of high-energy x-ray source laboratories in the United States (e.g., the National Synchrotron Light Source, the Stanford Synchrotron Radiation Laboratory, and the Advanced Photon Source), which allows simultaneous exposure of large numbers of PMMA template substrates.

The primary method of PMMA application is solvent bonding of a prefabricated sheet of low-strain material (Skrobis, Taylor, and Engelstad, 1995; Guckel, 1996), which minimizes the problem of high-strain fields in the PMMA. This method utilizes preforms cut from commercially supplied PMMA, which are attached to the substrate by a spun adhesion layer. The PMMA is then milled to the desired thickness. At present, this process is labor intensive and limits the throughput. Other methods of PMMA application have also been explored (Mohr, Ehrfeld, and Munchmeyer, 1988), as well as alternative materials for templates (polyimides). Because of the residual strain in the material, the utility of these methods is limited to tens of microns in thickness, however.

The total thickness of PMMA exposed is a function of the usable x-ray flux transmitted through the mask. The flux delivered for most synchrotrons at the wafer surface after the soft x-rays are filtered out is sufficient for only one PMMA layer of 500 μm or less per hour. To improve the exposure throughput, highly energetic sources (e.g., the National

Synchrotron Light Source) are used, increasing the exposure throughput by an order of magnitude or more.

Although electroplating of metals like nickel, copper, and permalloy have become mainstream manufacturing processes in the disk-drive industry, electroplating large numbers of wafers containing small, high-aspect ratio structures has not. Transporting plating reactants into 500 μm deep, 20 μm wide features stresses the state of the art in single-wafer and batch-electroplating systems. Another challenge is performing deep plating over a wafer surface with a variable plating area.

Ultimately, the utility of LIGA for commodity, mass-produced parts will probably be enhanced by the use of traditional replication methods, such as injection molding, embossing, and casting. Although throughput using these techniques is well known in the macro (millimeter and greater) domain, the problems of using them for microfabricated parts are not well understood. A significant effort is under way in Germany to implement mass replication techniques via modifications of existing production-molding equipment (Becker et al., 1986). Efforts have been hampered by a number of problems, including handling of the mold masters, injection- or embossing-pressure management, flow dynamics in the dimensions of LIGA molds, mold release, and mold lifetime.

Whether LIGA systems are produced by replication or batch-exposure methods, they generally require further assembly of multiple, submillimeter components. In fact, this microassembly requirement will probably determine whether or not the LIGA process is viable. Self-assembly techniques have been demonstrated in surface micromachining (Chapter 2), but they have not yet been demonstrated for LIGA, which is characterized by assembled tolerances of less than 1 μm.

Ongoing research is addressing many of the technical issues connected with LIGA. For example, the disk-drive industry has undertaken extensive research in batch-electroplating techniques that may be applicable to LIGA. A final challenge that LIGA must overcome is the synchrotron scare factor. Many companies are wary of processes that rely upon equipment they cannot install in their own factories or that is located at a government or university facility with a "questionable" commitment to commercial manufacturing (Markus et al., 1996). The scare factor will not be overcome until several successful commercial products have been demonstrated and supported.

MATERIALS AND PROCESSES FOR ENHANCED-FORCE MICROACTUATION

Microscale devices can be actuated by a variety of mechanisms. An important challenge for many MEMS applications, however, is to make microactuators that can deliver sizable forces and in some cases large displacements. In this section, mechanisms that can be implemented using thin-film materials are briefly discussed, including magnetic, piezoelectric, electrostrictive, magnetostrictive, and shape-memory alloy materials.

Materials

Magnetic Thin-Films

MEMS researchers are using magnetic materials primarily for the development of high-torque/high-force actuators. Torques of 10^{-5} Nm for rotational magnetic microactuators (Guckel et al, 1996a) and forces reaching to the mN range with displacements of 250 μm for linear actuators have been reported (Rogge et al., 1996). Actuating a magnetic element using an off-chip source provides a significant advantage in some MEMS designs (Sniegowski et al., 1996). Other concepts for MEMS in which a strong local magnetic field would be useful have been inhibited by the difficulty of supplying that field at the current levels available in ICs.

Most magnetic thin-film materials in MEMS are deposited by electroplating, which has been refined as a result of many years of experience in the large-scale commercial data-disk storage industry (e.g., Ahn et al., 1996). Films are typically nickel or alloys of nickel and iron. Techniques for integrating magnetic thin-films with an IC process have also been demonstrated (Guckel et al., 1993; Judy and Muller, 1996). Some results with sputtered films have also been reported (Yamashita et al., 1991), and both low-permeability nickel and high-permeability non-nickel alloys have been patterned into complex geometries with high-aspect ratios using the LIGA process (Guckel et al., 1994).

The promising results thus far make it likely that magnetic films will be added to IC-derived processes for MEMS, at least in some facilities. The progress made in research must still be qualified for commercial applications by demonstrating reliable long-term compatibility in an overall MEMS process.

Piezoelectric Films

Most large-force, large-deflection actuation materials are ferroic ceramics or metals with complex domain structures that are poised on an instability to give a large mechanical response to external fields or forces. Piezoelectric actuators made from ferroelectric PZT ($PbZr_{1-x}Ti_xO_3$) ceramics are the most widely used electromechanical transducers for sensing and actuating in larger-scale devices. In these materials, force and electric field are proportional. PZT films have been successfully laid down on silicon by sol-gel and vapor-phase methods.

Multilayer ceramic actuators are manufactured worldwide for use as micropositioners, printers, micromotors, vibration suppressers, hydraulic valves, automotive fuel injectors, and switches. But the fabrication of these devices is not directly compatible with silicon IC-process technology. The significant increase in force achievable with piezoelectric materials, however, has sparked considerable interest in methods for integrating PZT films directly into silicon MEMS processes. To illustrate the capability of materials, consider a microactuator with parallel electrodes 10 m apart and an electrode area of 100 mm^2. The force for an electrostatic actuator with an air gap between the electrodes is given by the Maxwell stress, s:

$$F_{electrostatic} = sA = -1/2\,A\,K_{air}\,e_o E^2 \qquad (1)$$

However, with poled PZT between the electrodes the maximum force is:

$$F_{piezoelectric} = sA = Ae_{33}E \qquad (2)$$

The ratio $F_{piezoelectric}/F_{electrostatic}$ is, therefore:

$$|F_{piezoelectric}/F_{electrostatic}| = 2e_{33}/Ke_o\,E \qquad (3)$$

In these expressions A is the electrode area, K is the dielectric constant, e_o is the permitivity of free space, e_{33} is the piezoelectric stress coefficient (~10 C/m^2 for PZT), and E is the electric field. For an electrostatic actuator, E_{max} is about 3 MV/m, which is the breakdown strength of air. For a piezoelectric ceramic, the depoling field provides a limit at about 3 MV/m, which is on the same order as typical insulator breakdown fields. Therefore, assuming a field of 10^6 V/m and using Ke_o equal to 3.456 x 10^{-11} F/m for silicon dioxide, Equation (3) predicts a ratio of roughly 6 x 10^5 for the two forces.

The foregoing example shows that piezoelectric actuators can provide enormous increases in output force compared to those available from electrostatic drives. Although the displacements are not very large for the parallel-plate, piezoelectric-electrode configuration (typically a few nanometers), a PZT-silicon-cantilever design or a flextensional moonie ("bellows") configuration used in macroscopic actuators can greatly amplify the motions by trading force for displacement. Achieving relatively large displacements and high forces simultaneously will probably require more elaborate structures (Zdeblick, 1996).

As MEMS applications proliferate, the ability to apply technologies derived from the multilayer ceramic-actuator field to the integrated, thin-film silicon MEMS field could become very important. Many problems exist, however, from the understanding of basic material properties and processing challenges to integrating these materials into more conventional IC-fabrication methodologies.

Shape-Memory Alloys

A number of intermetallic compounds exhibit a large shape-memory effect in which a deformed metal can be restored to its original ferroelastic shape when heated (Kuribayashi, 1986; Wayman, 1993). This behavior is a consequence of a ferroelastic phase transformation in which the structure changes from the multidomain martensitic state to the higher temperature austenite structure. Obtainable strain for the thermal-memory effect (Ni/Ti and Cu/Zn/Al) is approximately 4.5 percent for bulk material (Wayman, 1993). Shape-memory structures can have advantages, such as high work-to-mass ratios and noiseless and reliable operation, over conventional actuators. Shape-memory actuators are slow compared to piezoelectrics but offer recoverable strains up to 10 times greater than alternative approaches.

Researchers have attempted to fabricate actuators using thin-film-deposited Ni/Ti (NITINOL) as a shape-memory alloy (SMA; Busch, Johnson, and Lee, 1990; Walker, Gabriel, and Mehregany, 1990), but the results to date as to the viability of this approach are not conclusive (Miyazaki, 1990). NITINOL films have been sputtered to thicknesses between 0.2 and 50 μm on a variety of substrates, including silicon. When decoupled from the substrate, some films exhibit shape-recovery characteristics similar to those of bulk NITINOL. The films can be electrically driven using joule heating, and they demonstrate fast cooling rates because of the large surface-to-volume ratio. By selectively etching the shape-memory film and the silicon substrate, SMA microactuators have also been explored for use as electrically driven microvalves. The control of film composition and properties has proven difficult in sputter-deposited films, however, and further study of deposition techniques is needed.

Heat-actuated SMAs are being studied for use in a number of thin-film microdevices (Walker, Gabriel, and Mehregany, 1990). Applications are focused on actuators ranging from microrobotic manipulators to pneumatics for valves in which small TiNi ribbons are stretched to close a silicon-membrane gate. The principal advantages of SMA thin-film actuators are their ability to produce large forces and displacements within small volumes at voltages common in ICs. The availability of thin-film SMA material would greatly aid MEMS applications, but its development has been very slow. Another problem is the necessary local hot region, which can complicate its use in biological applications.

Shape-Memory Polymers

Shape-memory polymers are a relatively recent development (Liang, Rogers, and Malafeew, 1991; Hayashi, Ishikawa, and Jiordana, 1993). They are light, have good shape-recovery characteristics, and may be able to compete with shape-memory alloys in some MEMS applications

(Tobushi et al., 1996). The phase-transition temperature is near to room temperature in many of these materials. Considerable research is required to determine their possible application to MEMS, however.

Magnetostrictive Alloys

Magnetostrictive alloys like TERFENOL-D ($Tb_{1-x}Dy_xFe_2$) function well as sensors and actuators (Hathaway and Clark, 1993) in the macro scale. A large number of macroscale magnetomechanical transducers and actuators utilizing TERFENOL-D have been designed and manufactured. The high energy density of these actuators, plus their ruggedness and reliability, make them attractive for vibration suppression and high-power sonar. A macroscopic resonant magnetostrictive rotating motor has been reported that can produce a torque of 2 Nm at the low rotating speed of 100 degrees per second (Claeyssen, et al., 1996).

Thin films of magnetostrictive rare-earth/iron alloys can be sputtered on silicon and patterned by etching or sputtering through masks. Micropump and microvalve membranes and cantilevers are targeted MEMS components (Quandt, Gerlach, and Seemann, 1994), but little has been reported thus far on the incorporation of magnetostrictive materials into an IC-derived process.

Processing

Advances in the use of new materials, novel powder-synthesis methods, and ceramic integration are being made in electronic ceramics at scales much greater than those typical of MEMS. Monolithic multifunctional components take advantage of four existing technologies: thick-film methods and materials; multilayer ceramics capacitor processes; cofired package concepts; and thin-film deposition on silicon and other substrates.

Processing Multilayer Ceramics

Improved processing and manufacturing of multilayer ceramics, especially for capacitors and microelectronic packages, has resulted from research on the microstructural-property relationships of multilayer ceramics (Herbert, 1985). Fabrication techniques include powder processing, thin-sheet formation, and metallurgical interactions.

Multilayer capacitors and packaging currently make up more than half the electronic ceramics market. Although they cannot be directly integrated with ongoing IC-based MEMS efforts, these technologies can be transferred to the manufacture of multilayer actuators for submillimeter MEMS. More than 29 billion units are manufactured each year for multilayer capacitors and actuators, outnumbering by far any other electronic ceramic component. Multilayer ceramics and hybrid packages consist of alternating layers of dielectric and metal electrodes spaced about 10 to 20 μm apart. These ceramics have been applied to miniature valve- and pump-systems, using adhesive joints (Esashi and Matsumoto, 1991).

Fabrication technologies for all electronic ceramic materials have the same basic process steps, regardless of application. The steps are powder preparation, powder processing, green forming, and densification. A number of variations are used to obtain multilayer configurations for ceramic-metal composites.

Thin-Film Processing

With advances in thin-film technologies, various methods of depositing electroceramic components have been reported for the fabrication of sensors and actuators, capacitors, resistors, and magnetic materials on a variety of substrate materials. These methods can generally be divided into physical methods (Auciello, Krauss, and Gifford, 1996) and chemical methods. Physical methods include evaporation methods, molecular-beam epitaxy (MBE), liquid-phase epitaxy, plasma- and ion-beam sputter deposition (PSD and IBSD), and pulsed laser-ablation deposition (PLAD). Chemical methods include CVD (chemical-vapor deposition), metal-organic CVD (MOCVD), metal/organic decomposition (MOD), and sol-gel processing. Several published papers (Mansingh, 1990; Roy, Etzold, and Cuoma, 1990; Polla and Francis, 1996) have reviewed and compared the various thin-film preparation techniques. The techniques that have received the most research attention in recent years are described below.

The PLAD method provides good control of film stoichiometry and a high deposition-rate, but it is not suitable for conformal, large-area deposition in batch processing. A well known problem for the PLAD method is the production of macroscopic particles. Various CVD processes have been developed for making ferroelectric thin films with properties suitable for devices. CVD has distinct advantages over other deposition techniques, especially when uniform deposition over large areas is desirable. Good step coverage can generally be obtained by this technique, and it is the method of choice for fabricating thin-film devices, such as nonvolatile ferroelectric random access memories (NVFRAMs) and dynamic random access memories (DRAMs). One limitation of the CVD process for electroceramic thin films is the availability of suitable precursors. Several modifications have been derived to overcome this problem.

Solution deposition facilitates stoichiometric control of complex mixed oxides better than any other technique, including PSD and MOCVD. Solution deposition is an inexpensive method that may be compatible with semiconductor fabrication technologies, and efforts to adapt it to MEMS are under way. The most frequently used solution-preparation approaches can be grouped into three categories: sol-gel processes that use metal salts or alkoxides as precursors and 2-methoxyethanol as a reactant and solvent; MOD approaches that use large, water-insensitive carboxylate compounds; and hybrid processes that use chelating agents, such as acetic acid.

In addition to their use as actuators, ferroic materials are useful "coatings" for detecting changes in chemistry, temperature, humidity, and magnetic fields. Zinc oxide has been the most frequently deposited thin film on silicon. Table 3-1 lists some of the materials and applications that have been explored for ferroic materials.

The uses and limitations of ferroelectric thin films in MEMS applications have recently been reviewed (Polla and Francis, 1996). Two examples of devices that employ piezoelectrically driven materials are an inch-worm-driven microsurgical tool (Figure 3-4) and an ultrasonic cutter and spray nozzle (Lal and White, 1997).

Material-processing issues in the integration of these materials with IC-based silicon processing include: residual stress, planarization, encapsulation, adhesion, etching selectivity, electrode materials, thin-film cracking, and contamination. Adapting these processes to wafer-based manufacturing also presents significant challenges.

FILMS FOR USE IN SEVERE ENVIRONMENTS: SILICON CARBIDE AND DIAMOND

Applications have been identified in the automotive, electrical, and nuclear industries for MEMS sensors, actuators, and associated electronics that can operate in high-temperature and severe environments (e.g., car engines, auto tires, nuclear reactors, and nuclear waste storage facilities). Two potential thin-film materials for MEMS capable of withstanding severe environments are silicon carbide and diamond.

Silicon Carbide

Silicon carbide (SiC) is known both for its high-temperature semiconducting properties and for its radiation of recombination-induced light in the blue spectrum. A small amount of research has been conducted on SiC as a coating film and as a material possibly suitable for MEMS in high-temperature or severe environments (Klumpp et al., 1994; Fleischman et al., 1996; Mueller, 1993). Mehregany and his coworkers reported the deposition of high-quality, oriented SiC films on four-inch silicon wafers using a modified, cold-wall, rf-heated atmospheric-pressure CVD system (Fleischman et al., 1996). SiC films and suspended structures that appear to be amorphous were also made by plasma-enhanced CVD (Klumpp et al., 1994). Many challenges face the successful integration of SiC into IC-based MEMS processes, including the uniform deposition of known material over large wafer areas and the problem of developing high-rate techniques for patterning and etching.

Diamond

Carbon in diamond form as a film is of interest because of its chemical and biochemical inertness, its excellent thermal conductivity and mechanical hardness, and the low frictional effects at its surface. Because of these attractive features, several academic research groups in Europe have been working on

TABLE 3-1 Potential Electroceramic Sensor Materials

Sensor Type	Ceramic	Operation Mode
Oxygen Sensor	$Zr_{1-x}Ca_xO_{2-x}$	Ionic conduction caused by oxygen gradient
Humidity Sensor	$MgCr_2O_4$-TiO_2	Dissociation of adsorbed water molecules
pH Sensor	RuO_2	Reaction of protons with surface oxygen
Propane Sensor	SnO_2	Reduction of tin oxide
Negative Temperature Coefficient Thermistor	$Ni_{1-x}Li_xO$	p-type semiconductor with large thermally induced resistance change
Positive Temperature Coefficient Thermistor	$Ba_{1-x}La_xTiO_3$	Semiconducting behavior modified by ferroelectric transition
Varistor	ZnO-Bi_2O_3	Tunneling through thin insulating boundary
Magnetoresistor	$La_{1-x}Ca_xMnO_3$	Magnetic transition/resistance change

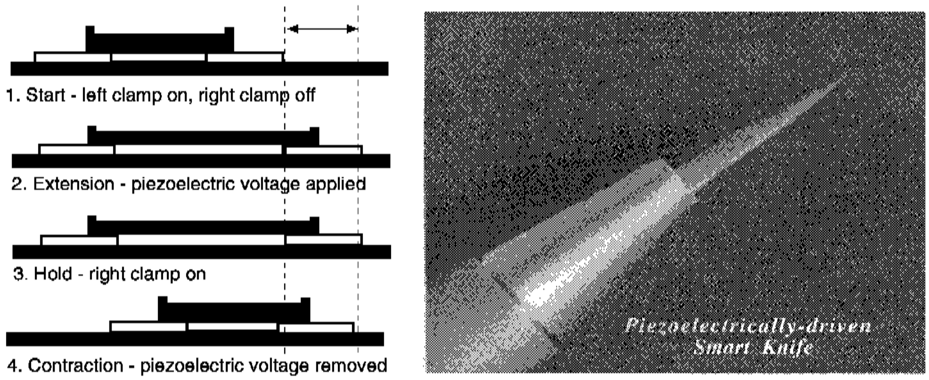

FIGURE 3-4 Microsurgical tool driven by piezoelectric materials. Source: D.L. Polla, University of Minnesota.

diamond films under a program sponsored by the European Community. Considerable work has also been done in the United States at Vanderbilt University and Michigan State University. Polycrystalline diamond films have been grown on silicon from very sparse mixtures of methane (1 percent) in hydrogen (99 percent) at 850°C at growth rates of 0.5 micrometer per hour. Diamond piezoresistors on a diamond diaphragm have been demonstrated as pressure sensors (Wur et al., 1993). Patterning the diamond films is difficult, however, and Wur used a lift-off technique in the cited work. Researchers have also demonstrated ArF excimer-laser ablation, ion etching, and electrolytic etching. Although much work is needed before diamond can be qualified as a mechanical material for MEMS, it may have applications as a low-friction coating material.

SURFACE MODIFICATIONS/COATINGS

Processes for surface modification (self-assembled monolayers [SAMs]), deposition, and patterning at submicron levels have been demonstrated for a number of materials. The key process step is the transfer of a catalyst (e.g., a palladium colloid; Xia et al., 1996) from an elastomeric "stamp" to the substrate. This provides the selective pattern for metallization. The overall process has several distinct features:

- Surface characteristics can be tuned by selecting appropriately functionalized SAMs (e.g., alkyl siloxanes provide hydrophobic surfaces).
- These surfaces can be subsequently patterned using a number of wet or dry IC processes (Kumar et al., 1995).

Many of the deposited films can subsequently be patterned using IC-based equipment and methods. Other surface modification approaches for specific applications, such as biocompatibility, include designing bioactive coatings via protein engineering (Martin, Jiang, and Buchko, 1997).

Plasma-Deposited Polymers

Plasma deposition of polymers results in materials with properties different from more conventionally synthesized polymer films (Yasuda, 1985). By modifying the plasma-processing parameters during film deposition, the properties can be tailored. Plasma-deposited films (e.g., parylene) can coat surfaces conformally, even if they have strongly varying three-dimensional topographies (which is an important feature for passivation coatings), mechanical flexibility, or interlayer dielectrics for ICs. For example, a way to plasma-deposit PMMA as a photoresist onto a three-dimensional structure in order to pattern that structure has been demonstrated (Guckel et al., 1988).

Plasma-deposited polymers can also be used as barrier layers, protective layers, or anti-reflection coatings. Pulsed-plasmas (PECVD) have been used to coat surfaces conformally with fluorocarbons (Teflon™-like films; Limb et al., 1996). The methods have been optimized (starting monomeric materials and deposition procedures) to yield film thicknesses of several microns on both planar and nonplanar substrates.

Polyimides

Polyimides are used extensively in IC applications as dielectric layers, masking materials for plasma etching, and alpha-particle protection layers in memory applications. Polyimides have a dielectric constant of about 3.5 and are typically spin-coated and then cured at about 350°C. Pre-imidized polyimides can be processed at lower temperatures. Polyimides can also be purchased in sheet form under the trade name Kapton™.

Polyimides may be used in the nearer term in MEMS applications as insulating layers, sensing layers (especially for moisture sensors), or flexible membranes. Barth, Bernard, and Angell (1985) and Beebe and Denton (1994) have reported the use of polyimide as a flexible membrane-support for diode arrays and in biomedical applications. Polyimides have also been used as structural materials for electrostatic actuators.

The major advantage of polyimides is their ease of processing, especially using plasma etching. A disadvantage of polyimides is moisture absorption. Although this is a positive feature for moisture-sensing applications, it can lead to long-term reliability problems, such as increased insulator conductivity, adhesion loss, and corrosion. A number of low-moisture uptake polymers (many of which are fluorinated) have been developed, however, and these can be used in applications where moisture uptake is expected and not desirable.

Conducting Polymers

Early work indicates a potential for using conducting polymers as active sensing or actuation material, based on the changes in elastic moduli, electrical conductivity, and electromagnetic absorption caused by electrochemical doping (Baughmann et al., 1991; Della Santa et al., 1996). Dimensional changes from 0.5 to 10 percent are possible with stimulation voltages an order of magnitude lower than those generally found in electrostatic or piezoelectric actuators, although with comparatively longer cycles times. Della Santa et al. (1996) reported on the use of polypyrole in a conducting-polymer pump diaphragm, but considerable work remains to be done to develop and characterize conducting polymers as useful MEMS materials.

POWER SUPPLIES

As MEMS find broader applications, the demand for autonomous systems will certainly increase. The power source would currently account for the largest part of an autonomous system, however. Thus, reducing the size of power supplies is critical to the design and production of autonomous systems. Research is required on the development of materials with higher energy storage, as well as materials for microscaled fuel cells or miniature combustion devices. In addition, there are opportunities for on-chip and in-module energy converters that can provide electric power from the conversion of electromagnetic radiation, mechanical vibration, or thermal variations.

An alternative approach would be to eliminate power sources and wiring systems entirely and focus on new technologies that could provide power, communication, and control of remote, distributed sensors. For example, power and information could be transmitted into an on-chip radio-frequency (RF) loop antenna, enabling wireless operation of the distributed systems. An alternative to RF is using solar cells and optical-modulation capability to communicate with and power the system remotely via lasers.

SUMMARY

Although using only standard IC materials and processes may produce products with the same levels of manufacturability and reliability as products associated with modern VLSI devices, new materials and processes will be required for applications requiring enhanced-force microactuation, high-aspect-ratio structures, severe-environment resistance, and enhanced surface properties. In general, future MEMS materials and processes research should be focused on (1) expanding the suite of materials available for IC-like processing and (2) advancing thin-film processing techniques.

Materials that are not usually used in IC processes include magnetic, piezoelectric, ferroelectric, and shape-memory materials. Actuating-force requirements for valve closures and motor drives, for example, are already drawing attention to the advantages such materials would bring to MEMS. Other developments, such as MEMS for optics, biological purposes, chemical-process controls, high-temperature applications, and other hostile environments, will inevitably draw attention to the need for an even broader range of materials.

During IC development, new materials are typically incorporated as thin films and are produced by a limited number of techniques (e.g., low-pressure CVD or sputtering). Many of these materials either do not show optimal mechanical properties in thin-film form or are difficult to deposit by typical IC-fabrication methods or are incompatible with the microelectronic IC process. For some MEMS designs, it is only possible to apply specialized materials either by incorporating them in a step prior to more conventional processing or by adding them after conventional processing. Either of these options raises the possibility that the technology will be substantially different from better known processing techniques.

Advances in thin-film technologies have enabled the deposition of electroceramic components for the fabrication of sensor and actuators, capacitors, resistors, and magnetic materials on a variety of substrate materials. The deposition techniques discussed in this chapter offer the means to produce thin films with a variety of tailorable properties and characteristics. Efforts are needed, however, to resolve challenges associated with using these techniques, such as those associated with residual stress, planarization, encapsulation, adhesion, etching selectivity, thin-film cracking, and contamination. Furthermore, adapting the processes discussed above to wafer-based manufacturing presents significant challenges. Finally, as will be discussed in the next chapter, materials for MEMS need to be better characterized; many thin-film materials that are used in the IC industry (e.g., aluminum, silicon dioxide, amorphous silicon, porous silicon, various other deposited and plated metals, and polyimide) have still not been extensively studied and evaluated for their applicability to MEMS.

Conclusion. The specialized materials and processes discussed in this chapter all require further research to make them compatible with IC-based materials and processes or to permit them to be at the back end or off line in special process areas that will not add prohibitive costs or processing penalties to products. Extending the list of materials for MEMS that can be processed using lithography-based, IC-compatible techniques will be beneficial to MEMS development, provided that a thorough understanding of the properties of these materials is developed. Materials and techniques that might be able to be incorporated into IC-based MEMS in the nearer term include polyimides, magnetic thin films, HEXSIL, and piezoelectrics.

Recommendation. Research and development should be encouraged to develop new materials that extend the capabilities of MEMS. The new materials should be capable of being integrated, at some level, with conventional IC-based processing.

Recommendation. Research should be encouraged to develop techniques to produce repeatable, high-quality, batch-processed thin films of specialized materials and to determine the dependence of their properties on film-preparation techniques. For some materials, it may be advisable to establish "foundries" that can be used by the entire MEMS community and can serve as repositories for equipment and know-how.

Recommendation. The characterization and testing of MEMS materials should be an area of major emphasis. Studies that address fundamental mechanical properties (e.g., Young's modulus, fatigue strength, residual stress, internal friction) and the engineering physics of long-term reliability, friction, and wear are vitally needed. It is important that these studies take into account process, scaling, temperature, operational environment (i.e., vacuum, gaseous, or liquid), and size dependencies. Studies of the size effects of physical elements, on a scale comparable to the crystallite regions in a polycrystalline material, are required.

4

Designing Microelectromechanical Systems

The previous two chapters discussed the materials and fabrication techniques required for the production of MEMS. This chapter focuses on building an information and manufacturing infrastructure that will spur the development of MEMS, specifically metrology, modeling, CAD systems, and foundry facilities.

METROLOGY

Metrology is an area that is just being established in MEMS. The IC industry has been well supported by an extensive, constantly expanding understanding of the behavior of silicon and related materials as they are scaled down. No comparable resource exists for MEMS, however. Many areas of research are required to understand the nature and properties of materials used in MEMS. For example, an extensive knowledge-base exists of the electrical properties of polysilicon thin films, but knowledge about their micromechanical properties is limited as is detailed knowledge of the long-term reliability of mechanically stressed polysilicon or the surface mechanics related to friction, wear, corrosion, and stress-related failure. There is a similar lack of fundamental understanding about other thin-film materials borrowed from the electrical domain and now exercised mechanically (e.g., silicon nitride, silicon dioxide, and thin-film metals). The properties (e.g., strength and surface chemistry) of materials configured at the small scales of MEMS can influence the behavior of the devices of which they are integral parts, and material behavior crosses the boundary from volume or bulk effects to surface-driven effects. For example, frictional effects, in contrast to inertial effects, take on overwhelming importance in small mechanical systems.[1] As MEMS enable the creation of fluid systems with smaller and smaller flow (signal) levels, understanding the nature of fluids in micrometer-sized channels and cavities becomes crucial. In general, a thorough understanding is needed of the mechanical properties of the materials to be used in MEMS at appropriate scales. Studies of the size effects associated with physical elements that approach the size of one-to-several grains would be useful.

Measurements of MEMS mechanical elements are a challenge to the metrology equipment currently available. For example, optical measurement systems require trade-offs between feature size and depth of focus, and scanning electron microscope (SEM) measurement systems have limited working distances and also difficulty measuring nonconducting materials. It is often desirable in MEMS to measure physical dimensions (e.g., thickness and lateral extent) and other parameters (e.g., bow, warp, or surface roughness) simultaneously. There are also cases where the parameters are not directly visible. In these cases, the characterization of MEMS has been aided by high-resolution, time-resolved, visual inspection capabilities, such as the x-ray imaging system developed at the SRI Sarnoff Laboratories. This system makes the flow through chambers and valves in microfluidic systems visible (Lanzillotto et al., 1996) and is an important tool for characterizing MEMS.

In addition to methods of testing materials and measuring structural tolerances, devices are also required that can determine the mechanical properties of MEMS devices, demonstrate mechanical-device repeatability and reliability, and facilitate quality-control practices. Package-level testing is currently the most common way to measure MEMS performance, but the development of in-process wafer-level testing is clearly necessary for low-cost manufacture. Wafer-level testing of MEMS presents special challenges that are often product dependent.

Generic test-structures that indicate basic mechanical properties of MEMS materials at the wafer level can (and should) be developed and characterized. In the IC industry, parametric wafer-screening methods have been developed based on knowledge of the effects of process variations on the performance of electronic devices and systems. Similar methods should be developed to support the growth of MEMS. Agreement will have to be reached on (1) the structures to monitor the mechanical and materials properties that are most critical to micromechanical performance and (2) the methods of testing and characterizing them.

Methods of testing and characterizing MEMS should be standardized. The development of standards, like the standards in the American Society for Testing and Materials (ASTM) or Institute of Electrical and Electronics Engineers

[1] A useful comparison is the evolved nature of small living animals. Insect motions and mechanisms can offer important insights to MEMS designers. Some MEMS engineers in Japan have already used analogies to insects for design purposes.

(IEEE), is necessary to support commercialization and foundry technologies. An effective fabrication facility needs to be able to provide a valid assessment of the characteristics and behavior of materials and processes that potential customers can use as a basis for comparing facilities. The same parameters can be used to facilitate reasonable modeling and simulation of designs prior to fabrication. The ability to deposit, characterize, and test a material or device must not depend on the skill or equipment of a single organization.

MODELING

A particular challenge for MEMS is the establishment of a self-contained, complete, and integrated modeling and simulation suite appropriate to its computational analysis requirements. Most MEMS analyses to date have required numerical techniques based on methods using discrete data. Commercial mechanical-engineering and finite-element analysis (FEA) software has proven useful for modeling a variety of parameters (e.g., displacement, stress, electric field, magnetic field, temperature, and fluid velocity) under a wide variety of conditions. For example, FEA-based modal analysis has often been used to model the mechanical-vibration modes of structures.

MEMS-specific tools will be required, however, and these tools will have to be integrated into an environment where complete structural, as well as operational, analysis can be performed. Academic research systems (e.g., MEMCAD [Senturia et al, 1992] and CAEMEMS [Crary, Juma, and Zhang, 1991]) and small-business spin-offs from academe (e.g., IntelliSense and Microcosim)—many of which are supported by general and newly CAD-focused programs at DARPA—have begun to address the need for an easy-to-use interface between modeler and numerical tools. But much remains to be done.

The need for numerical tools that deal efficiently with cross-energy domain modeling is also beginning to be addressed (e.g., Wachutka, 1995). Commercial tools are coming to market that can treat some problems involving the coupled solutions of displacement, stress, electrostatic, and temperature fields (IntelliSense). But these tools are in early development. Accurate predictions of the energy dissipation and mechanical quality factors of MEMS structures are still elusive and also require further research.

COMPUTER-AIDED DESIGN SYSTEMS

MEMS devices have not yet been designed using CAD and computer-aided engineering (CAE) tools directly, in contrast to the more mature IC devices (Antonsson, 1996). Computer tools familiar in the IC-design world, such as schematic capture, schematic-to-layout generation, automatic routing, and design verification, need to be developed for MEMS. There is also a need for software tools designed for different tasks (e.g., layout, solid modeling, discretization, numerical computation, and visualization) that can function synergistically under a consistent user interface. Newer software techniques, such as object-oriented methods, will make it easier for solutions developed in one domain to be adopted in several others. For MEMS to flourish, computer descriptions will be needed for geometric, kinematic, and field views, as well as for layout and function. Other desirable features of an evolving system for CAD/CAE for MEMS include efficient interactive operation; modularity; flexibility to allow for changes; reliability; accuracy control, including error propagation from material-property and geometric uncertainties; and methods for discretization and for estimating numerical errors. Designers will eventually need to be able to determine such information as the cost of manufacture or the expected time to failure. A MEMS compiler that can start from a user specification and produce masking and processing information as outputs also needs to be developed.

Existing commercial CAD frameworks can provide a starting point for a MEMS CAD system (Broenink, Bekkink, and Breedveld, 1992; Gilbert et al., 1993; Beerschwinger et al, 1994; Senturia, 1995), but the great diversity of MEMS devices and implementations means that libraries of parameterized MEMS devices will be very large. Systems will have to be able to manipulate and gain access to very large data banks of hundreds of types of devices, with tens to hundreds of parameters each. Thus, an efficient means of library generation, organization, and accessibility is essential. Detailed process and materials information to model and simulate MEMS devices and systems accurately are also required. Unfortunately, material parameters change from fabrication facility to fabrication facility, so the CAD package will have to keep track of where the devices are to be made.

FOUNDRY INFRASTRUCTURE

To assure industry and government users that they will be able to manufacture future MEMS products at competitive rates, the United States will have to develop a MEMS foundry-technology base similar to the base that supports the IC markets. Several elements of the infrastructure will have to be developed concurrently to create this technology base, the most important being the CAD infrastructure, which is the backbone of the foundry interface. A processing base must be developed so that foundries will be able to provide "technology files" to prospective users. These files must adequately describe the foundry technologies in terms of layout rules, modeling and simulation parameters, and behavioral characteristics (e.g., materials parameters). Qualified data regarding behavioral characteristics need to be made available to the user, who can then independently develop a system and submit only a design-language file to the foundry. Ultimately, a compendium of data similar to the database available for ICs (Beadle, Tsai, and Plummer, 1985) will be necessary for MEMS. An important role for foundries will be to assist in the systematic development of computer-aided processing models, which could be integrated with CAD models and would aid in determining the interrelationships among requirements and in-process inspection parameters.

Many industries have also been strengthened by adopting *flexible manufacturing*, which are fabrication processes for which adding or removing individual process steps is an easy design option. The underlying reason for this trend is economic because the ability to adjust to changing market conditions and customer requirements in real time is often the key to success. Flexible manufacturing principles may also be valuable to the MEMS industry, especially in cases of relatively low volumes and numbers of specialty processes. Whereas variations in IC devices and performance can often be made through changes in layout, the physical and mechanical natures of MEMS will also require that variability in processes be available to produce families of devices. In contrast to IC manufacturing, MEMS production can be expected to be in relatively small lots, at least initially. Economies of scale can more easily be achieved if common processes are standard to a facility or foundry, and process steps unique to each design can be efficiently added or omitted. In the flexible manufacturing environment, it should be possible to include higher-capability steps and advanced materials when and where they are needed.

The advancement of flexible manufacturing for MEMS foundries presents formidable challenges. Meeting them successfully will strongly affect the commercialization of MEMS designs. One area that will particularly benefit from flexible manufacturing is higher force and displacement actuation. In many cases, achieving higher forces and displacements in MEMS requires using materials not used in the conventional IC industry (see Chapter 3). Using these materials in commercial systems will require the introduction of appropriate processing methods, and incorporating these methods into flexible manufacturing foundries would be a significant advance for MEMS.

Work on developing a foundry infrastructure includes the DARPA-supported MEMS Infrastructure programs at MCNC, Analog Devices, and Sandia and the custom prototyping and manufacturing capabilities at organizations such as IC Sensors, NovaSensor, Silicon Microstructures, and others.

The establishment of standard processes and foundries for MEMS depends on a complex set of issues but is essential in the near future to support the growth of MEMS from the prototype and low-volume commercial level to the volume-driven, low-cost commercial regime. Several standard-process MEMS foundries need to be available to enable companies with no wafer-processing capabilities to enter the field. MEMS applications exist for consumer, automotive, aerospace, and medical products so access to foundries will be essential. Custom, flexible fabrication facilities must also be available, however, for users who require access and manipulation of the process to produce and optimize their products. In the IC industry, these facilities have been best organized at universities and national laboratories, where not-for-profit development is more acceptable.

SUMMARY

Rapid development in the IC industry has been aided by the establishment of a foundry infrastructure that ensures that industry and government users will be able to manufacture IC products at competitive rates and enables companies that do not have wafer-processing capabilities to enter the field. One of the key factors in the development of the IC foundry infrastructure was the development of a CAD infrastructure that became the backbone of the foundry interface. Design methods were implemented that allowed IC designers to develop systems independently and then have them manufactured by submitting only a design-language file. The MEMS field is more complicated because of the broad range of electrical and mechanical applications, including consumer, automotive, aerospace, and medical products. Thus, several standard-process MEMS foundries would have to be available and accessible, as well as custom, flexible fabrication facilities for users who require access to and manipulation of the process to produce and optimize their products.

The development of the MEMS field will be greatly aided by the development of an extensive information infrastructure that includes the adoption of a generally accepted set of standards and metrics, the establishment of advanced modeling and computer-design tools, and the establishment of foundries that can support the most promising generic MEMS processes.

The committee recognizes that realizing MEMS foundries may be difficult because many commercial companies have difficulty seeing "what's in it for them." Besides the danger of compromising proprietary know-how, companies offering a foundry service will have to commit to specific processes and reasonable turnaround schedules. In the instances where small industries have tried to accommodate MEMS foundry runs so far, the results have not been warmly appreciated. A more feasible road to at least moderate success at the present juncture appears to be using academic and government laboratories to provide foundry services. The recent expansion of the National Nanofabrication Laboratory to sites at several universities and the capabilities of national laboratories, like Sandia and Livermore, may provide opportunities for MEMS foundries of a different nature, where direct hands-on work can be done by the MEMS researcher. This kind of operation could not be as widely extended as the more traditional foundry approach of MCNC, which interacts with users only through exchanges of software, but it may provide an interim avenue until specific areas in the MEMS field are further developed.

Conclusion. Establishing standard CAD and foundry infrastructure for MEMS is essential in the near future to support the growth of MEMS from the prototype and low-volume commercial level to the volume-driven, low-cost commercial level. The development of a MEMS foundry-technology base, similar to the base that supports ICs, would assure users that MEMS products can be manufactured at competitive rates and would enable small companies and research organizations to enter the field.

Recommendation. A MEMS CAD-infrastructure that extends from processing and basic modeling to full system-design capabilities should be established. A process technology infrastructure (e.g., electrical, mechanical, fluid, chemical, etc. and their integration to form complete systems) that is widely available to MEMS designers and product engineers should be developed.

5

Assembly, Packaging, and Testing

Cost reduction is the most prominent challenge facing the assembly and packaging of MEMS. Packaging currently represents more than 80 percent of the cost of some systems and is often the leading cause of system failure. MEMS packaging is usually approached by individual manufacturers on a specialized, application-specific basis in which problems are solved independently. Very little publicly available work has been conducted on the basic aspects of generic packaging and assembly or on standardized packaging methodologies for MEMS. The imbalance between the ease with which batch-fabricated MEMS can be produced and the difficulty and cost of packaging and testing them limits the speed with which new MEMS can be introduced into the market.

MEMS chip technologies have developed rapidly largely because they share common procedures with conventional microelectronics chip processing. The assembly, packaging, and testing (AP&T) of MEMS, however, often require radical departures from the "normal" approaches used for electronics. MEMS components may need to interface with light, fluid pressure, chemical species, and other media without harming the MEMS or the associated electronics. Not surprisingly, meeting these needs requires specialized AP&T approaches, making commonality and cost-effectiveness problematic.

Approaches to MEMS AP&T should make use of the existing semiconductor-industry infrastructure wherever possible. The assembly and packaging equipment infrastructure (beyond those available in the IC industry) should evolve as the volume of commercial applications for MEMS provides market support. Unfortunately, this leaves the pioneers in the field to fend for themselves. They must rely either on their own engineering skills or on attracting the attention of equipment-manufacturing partners. Apparently small departures from conventional electronic-chip practices (e.g., the changes necessary for dicing accelerometer wafers into individual chips) can result in high incremental expenses and costly development delays.

Creating families of generic, standardized, modular AP&T approaches for different classes of MEMS devices could accelerate the overall pace of development. This goal may be inconsistent with low cost, rapid development in the short term, but in the long term it will undoubtedly advance the field. This chapter examines the problems associated with present AP&T methods, considers some of the outstanding needs, and discusses both generic and application-specific approaches.

CONTRASTS BETWEEN ASSEMBLY, PACKAGING, AND TESTING OF INTEGRATED CIRCUITS AND MICROELECTROMECHANICAL SYSTEMS

The electronics industry has expended considerable resources on the development of AP&T techniques for microelectronic circuits, many of which can be applied to MEMS. MEMS typically require extra attention, however, because MEMS often process nonelectronic signals. These signals must be transmitted through the package (when the signal should affect the MEMS), while other parameters must be either transmitted (when the MEMS can tolerate exposure to that parameter) or rejected by the package (when the parameter is not desired or cannot be tolerated). Parameter selection is never perfect, however, and system specifications typically define the allowable cross-talk between desirable and undesirable parameters. A simple diagram of packaging requirements for a MEMS (Figure 5-1) provides a conceptual framework for the packaging requirements and assembly and test methods for MEMS. Determining which parameters are desirable, tolerable, and undesirable, and incorporating this into the design is not a straightforward process, however.

To appreciate the problem, consider a single-domain problem in the electronics industry, "grounding and shielding" for electronic components. Take, as an example, the analog-to-digital converter (A/D), which must maintain a stable, accurate reference voltage on the chip for comparison to incoming signals. The voltage signal is the desired parameter, and all other signals are either tolerated or rejected. Undesirable parameters might, for example, include environmentally caused electrostatic signals or voltages that arise from mechanical stresses that lead to resistance variations via piezoresistive coefficients. Tolerated signals typically include temperature and magnetic field, but the A/D can be made insensitive to both of these by proper design.

MEMS typically include subcomponents that provide transduction between two signal domains. Some examples are:

- an electrostatic comb-drive in which an AC voltage drives a flexure-supported movable part (e.g., Tang, 1990) or a moving capacitor plate that converts mechanical motions into electrical signals (e.g., Analog Devices, Inc.)

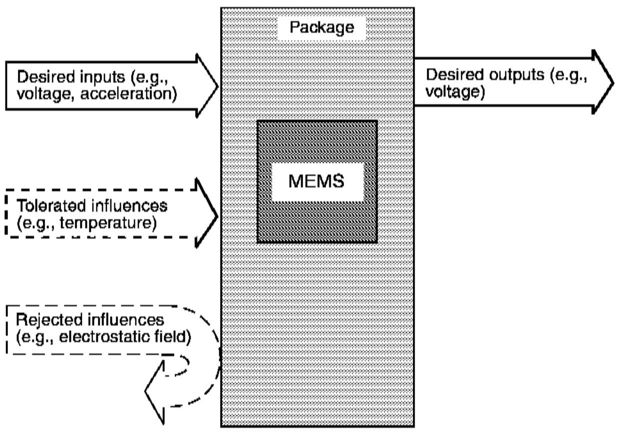

FIGURE 5-1 Block diagram of generic packaging requirements.

- an impact motor that converts a mechanical resonance into a linear motion (e.g., Lee et al., 1993; Daneman et al., 1995)
- a microvalve that converts electrical energy to thermo-pneumatic force (e.g., Zdeblick, 1996)
- a microanemometer that converts fluid flow into an electrical signal (e.g., Tai, 1996)
- a flexure beam that converts a mechanical motion to a light modulation (e.g., TI's DMD)

It is vital that the MEMS be designed to be insensitive to unwanted parameters first and then that the package be designed to admit the desired signal variables (e.g., fluid, thermal, inertial, or optical) with minimal distortion, while screening out unwanted variables. At the same time, reasonable cost, robustness for the intended application, and good manufacturing characteristics, including acceptable AP&T properties, must be achieved. These engineering problems must be solved in order for MEMS to compete successfully with alternative system designs.

INTERFACES

The interfaces between a MEMS component and its operating environment are often troublesome and may present considerable design and manufacturing challenges. Signals admitted to the MEMS package may come from many sources, including electrical, thermal, inertial, fluid, chemical, and optical domains. Output can also vary greatly. Examples include electrical, optical, mechanical, chemical, hydraulic, and magnetic signals (Figure 5-2). Conduits into and out of the packaged MEMS for these signals must be designed to avoid distortion.

The difficulties of designing interfaces vary with the nature of the MEMS. Accelerometer interfacing is relatively easy because it requires only proper orientation and rigid mounting. Interfacing a pressure-sensing MEMS is usually harder because it requires resistance to corrosion from the working fluid and protection against excessive pressures. Chemical-sensor interfacing is inherently difficult, and chemical sensors often fail to provide good long-term stability. Interface considerations can be conceptually segregated into considerations of the chip package, the package environment, and the chip environment. Considerations for interfaces in the biomedical, optical, electric power, fluid, and mechanical domains are discussed below.

Biomedical Interfaces

The long-term impact of MEMS in the biomedical field is likely to be very strong. One application that has already

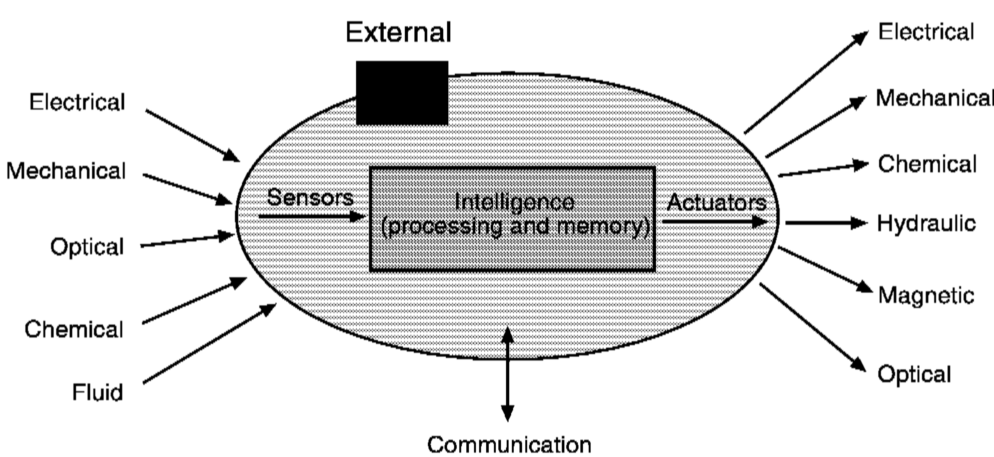

FIGURE 5-2 Schematic diagram summarizing various input/output modalities for MEMS systems. Source: Adapted from a figure by H. Zappe, The IBM Almaden Research Center.

appeared on the horizon is the biochemical laboratory on a chip. Another application is MEMS that would be part of instrumented catheters and endoscopes that could conduct in-body tests and, possibly, therapies. A third application is MEMS elements that might be embedded in living tissue, as pacemakers are. These three applications clearly have different interfaces.

Bringing MEMS technology into the diagnostic/medical market encompasses a number of additional complexities. As mentioned in Chapter 3, a number of efforts are under way to explore new materials and coatings that could increase the applications of MEMS. For regulated medical markets, the packaged test will need approvals that not only demonstrate performance but biocompatibility for specified lifetimes. Furthermore, critical-path testing (e.g., in a hospital environment) requires serviceability within 24 hours.

In the application nearest to commercial reality—the biochemical laboratory on a chip—the silicon surface is partitioned into many small cells, typically smaller than 0.1 mm on one square side. Successive reactions of a small quantity of an analyte with a reagent are initiated in these cells. In at least one version, the outcome is detected by optical means so that a large number of chemical tests can be done in a small, portable unit. Interfaces in MEMS built with these cells must (1) be inert to chemical attack for the useful lifetime of the chip, (2) allow controlled chemical mixing, and (3) allow reliable interrogation of the results. The interfaces are very specialized to the specific uses of the chip. MEMS incorporated into instrumented catheters or endoscopes, as well as MEMS designed for *in vivo* use, have additional constraints because they will interface with living tissue. There is little doubt that MEMS will play an important role in biomedicine, but it is also clear that considerable work still needs to be done to characterize interfaces for biomedical MEMS.

Optical Interfaces

Current work in the area of optical MEMS is directed toward two goals: building new types of displays based on physical motions of reflecting surfaces; and building new types of fiber-optic systems in which MEMS structures interact with directed light beams. In both cases, the MEMS package must pass light to a surface with which it will interact. Building similar packages has been done for a long time in the IC and photonics industries, which have produced commercial products such as solar cells, LEDs (light-emitting diodes), laser diodes, and light-alterable memory planes (as in the Intel FAMOS chips). Special techniques for surface-micromachining MEMS using free-standing silicon nitride films have been demonstrated (Mastrangelo, Muller, and Kumar, 1991), but details of processing, coatings, and coupling to fiber-optic inputs are still in the research stage.

Electrical Power

Insulating, grounding, and shielding electrical components at low-voltage levels are well understood from the electronics industry. Actuators, however, often require drivers that deliver 50 volts or more. The interfaces among the components, the package, and the environment for microdevices operating at these relatively high voltages cannot always be derived directly from typical IC power supplies. Corrosion problems can threaten the operation of MEMS powering systems because of the different operating environments in which the systems may operate and because not all MEMS devices can be hermetically isolated.

Fluidics

Coupling fluids into and out of MEMS presents significant challenges to systems integrators. Working fluids can range from inert gases (e.g., flow controllers for benign gases) to corrosive or toxic chemicals (e.g., pressure regulators on some gas chromatographs). Often the interface between the fluid and the MEMS requires a compression fitting (e.g., an O-ring seal) or a capillary tube inserted and glued to mate with a micromachined channel. Developing reliable manufacturing methods for interfacing MEMS with fluids requires continued work to support this rapidly growing application area.

The importance of the field of microfluidics is also becoming generally recognized. For example, DARPA has stressed the need for understanding the design rules and fluid dynamics on the MEMS scale from the early stages of their MEMS program funding for visualization tools to the recent Broad Agency Announcements in the MicroFlumes and related CAD-tools program. Critical elements for chemical and biochemical applications require precise fluid delivery, thermal and environmental isolation, and mixing, as well as materials compatibility for applications and solvent systems. Materials and geometries that can provide specified functions are being addressed at an increasing pace in academic and industrial settings (e.g., monthly conferences on methods and applications sponsored by International Business Communications (IBC) and the Association for Computing Machinery/Special Interest Group on Computer-Human Interactions (ASM/SIGCHI)). Two emerging issues are cost and whether functionality can be integrated on a single device (e.g., lab-on-a-chip) or by coupling high-value elements with generic microconnector elements. These issues are helping drive the exploration of novel materials and methods (see Chapter 3).

Mechanical Interfaces

Thus far, mechanical forces, or torques, are usually transmitted within a MEMS (e.g., in driven gears, as reported by

Sandia Corporation, or in air-driven Pelton wheels made at Bell Laboratories). For applications such as microrobots, movable magnetic read/write heads in a microdisk drive, or MEMS fluidic controls, forces and/or torques must be transmitted as a MEMS output. One approach has been to actuate large arrays of bimorph benders that work in parallel to produce cilia-type motions (Ataka et al., 1993). To make these motions more robust, the Fujita laboratory (where the cilia work was done) has constructed "loop actuators" from sputtered shape-memory-alloy films (Nakamura et al., 1997). More work is being done in this area in Japan than in the United States, but a good deal more research will be needed to produce practical MEMS with output mechanical interfaces.

PACKAGING

The needs for MEMS packaging are as diverse as the applications for which the systems can be used. Some examples include:

- silicon microvalves for gas flow control, some of which are packaged in an almost standard transistor outline (TO8) electrical chip package (e.g., Redwood package fittings)
- i-STAT blood-chemistry sensor (Chapter 1), which includes in-package calibration mixtures

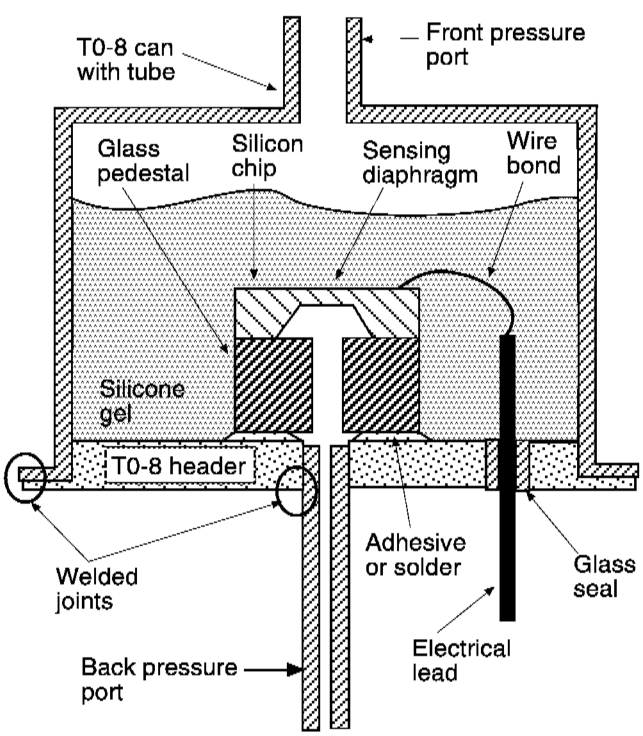

FIGURE 5-3 Silicon pressure sensor. Source: Mallon et al., 1988.

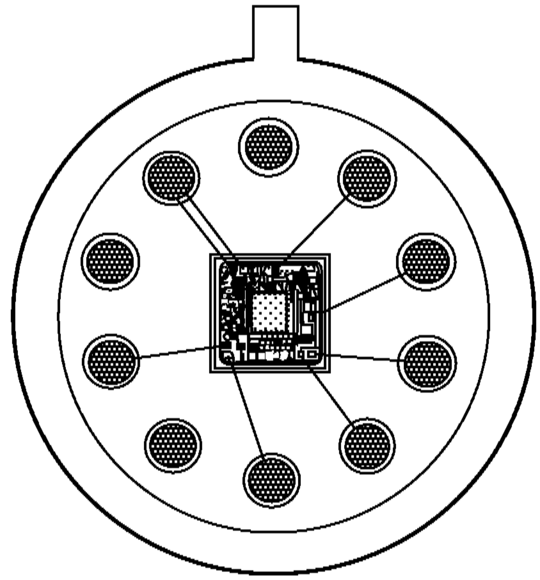

FIGURE 5-4 Accelerometer packaged in IC standard transistor outline (TO) package. Source: Analog Devices, Inc.

- pressure-sensing MEMS, for which a multitude of packages are used from many different manufacturers (e.g., Motorola, Honeywell, Kulite, EG&G IC Sensors, NovaSensor, Sensym, Foxboro, and Schlumberger; Figure 5-3)
- accelerometers, which are typically packaged in IC standard transistor outline (TO) and dual in-line (DIP) packages (e.g., Analog Devices, Ford, and Motorola; Figures 5-4, 5-5, 5-6 and Figure 1-5)

Specialized packaging with optically transmissive windows has been developed for TI's DMD chips (Chapter 1).

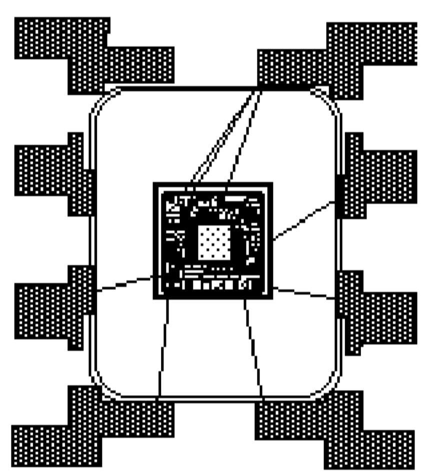

FIGURE 5-5 Accelerometer packaged in IC standard dual in-line (DIP) package. Source: Analog Devices, Inc.

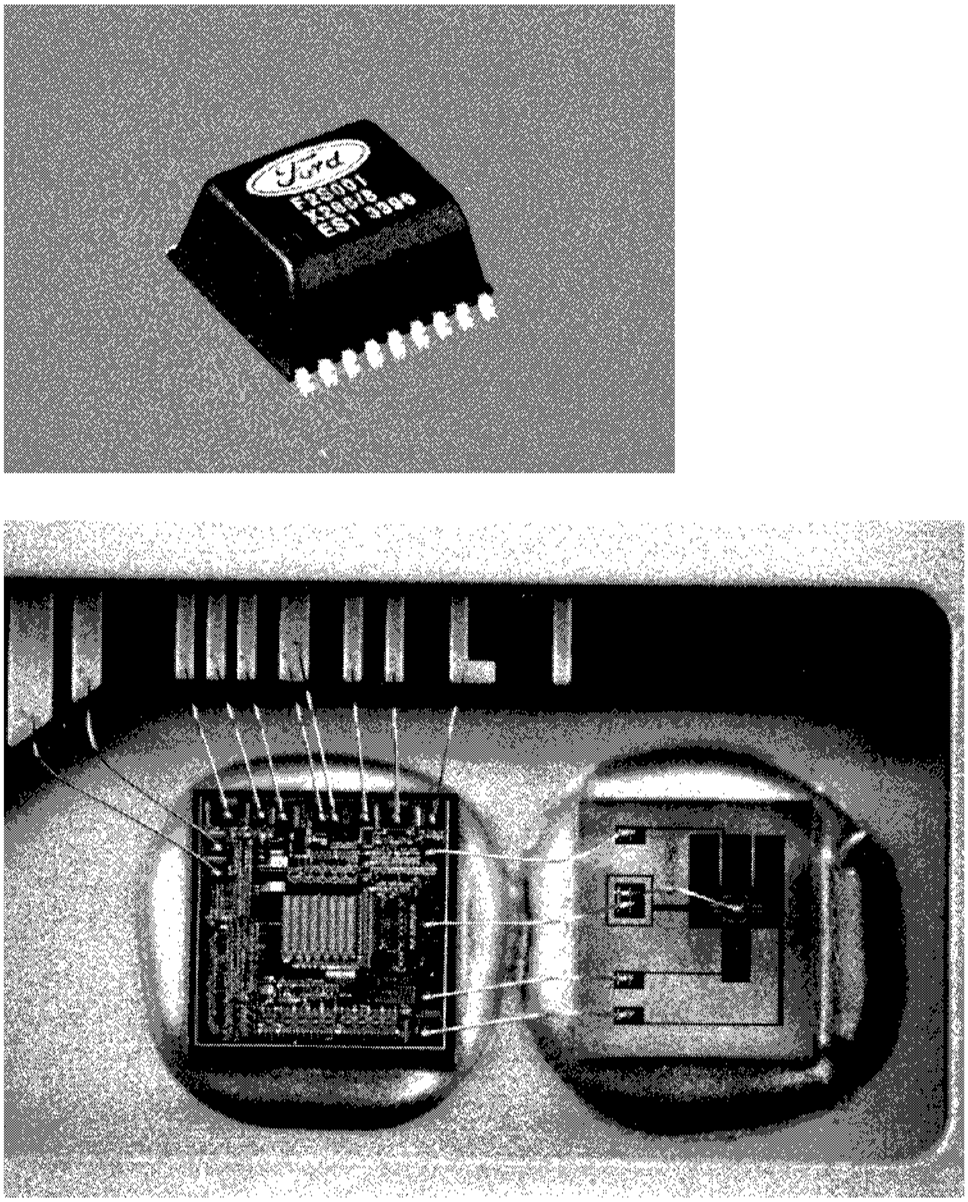

FIGURE 5-6 Two-chip smart accelerometer. The electronic functions are integrated with the sensing function through wire-bond interconnections. Source: Ford Microelectronics.

Ink-jet chips are typically attached to Kapton tape with embedded conductors and contact pads, which can then be glued to the plastic or metal plate in which the ink-jet pen is formed.

The development of packaging is open to creative ideas to enhance performance, and the evolution of packages is often simpler and quicker in practice than making design changes at the MEMS chip level. To date, however, most package development has been for specific products and applications, and very little "generic" packaging methodology has evolved. The development of generic packaging methodologies would eliminate duplication and the reworking of old problems for each new MEMS venture. Although it is not likely that just a few approaches to packaging MEMS will be sufficient, a set of capabilities and methodologies can be defined and developed that address the needs of each basic sensing and actuation domain (e.g., fluid handling, optical coupling, mechanical integration). Generic packaging methodologies would also stimulate the development of packaging equipment that could meet specific MEMS requirements.

Packaging also requires disciplined manufacturing and adequate testing, independent of MEMS manufacturing and testing. Partitioning costs between chip and package will have to be determined on a case-by-case basis. Not much has been published on these issues and associated problems, but there is a good deal of engineering know-how in the electronics, sensors, and actuators industries. The sections below briefly describe some of the issues involved.

Handling Issues

In many cases, MEMS contain moving parts that are fragile and that may not be protected through the standard IC-wafer passivation step. Because of their vulnerability, extra care must be taken with them. For placement, IC dice can be handled by vacuum pickups that attach to the top surface of the chip. But vacuum pickups may be unacceptable for MEMS dice because of their generally nonplanar surfaces. Some manufacturers have found ways of using conventional handling equipment for MEMS chips by modifying it to account for specific MEMS sensitivities.

Dicing

For components that are bulk micromachined, the deep-etching techniques used as part of the process can sometimes be used to partially or fully separate an individual die from the wafer during the machining process. Another technique that can be used with some devices is bonding an additional wafer or wafers to the first micromachined wafer and then separating the protected sandwiched structures. Many structures that are bulk micromachined cannot be handled in these ways, however, and other techniques must be found for separating dice without damaging or rupturing sensitive structures (e.g., diaphragms) or inadvertently depositing silicon particulates in, around, or under sensitive structures. There are similar problems with parts that are surface micromachined, which has encouraged efforts to encapsulate mechanical parts locally prior to separating the wafer into dice.

Four generic approaches to dicing MEMS wafers have been used. The first approach is to cover the structure with a permanent cap (e.g., Motorola uses this technique for the MAS40 accelerometer). This protects the micromechanical parts so that standard separation techniques can be used, although another piece of silicon—or other material—and additional processing are necessary. There are a number of opportunities for innovations in capping techniques, in the choice of materials for the cover, in the sealing methods, and in the configuration of the protective cover used for interconnection or for active devices or circuits. An interesting innovation is the formation of caps by surface micromachining a mold using HEXSIL (Cohn et al., 1996).

A second approach to MEMS wafer dicing is releasing the mechanical elements after the wafers have been sawed in the standard fashion. Sacrificial release materials and etchants are being investigated that would then allow the release step to be performed after the preliminary packaging steps (e.g., XeF_2 post-package release). One drawback of processing dice instead of wafers is that it rules out wafer-level testing because the unreleased MEMS devices are not functional at the wafer level.

A third MEMS-dicing approach is covering the moving elements with a sacrificial layer that can tolerate sawing or laser scribing and then removing it in a subsequent step. This dicing method also requires processing dice separately and makes wafer testing difficult or impossible. An advantage of this approach is that the sacrificial films are typically polymers, for which dry removal techniques are available (e.g., TI's DMD).

A fourth way to dice MEMS wafers is to protect the released structures with temporary stand-off housings. After sawing and cleaning the wafer using more-or-less standard tooling, the temporary covers are removed. This approach involves extra steps but has the virtue of keeping all steps in a batch-fabrication mode. Analog Devices, Inc., uses this procedure in the fabrication of the ADXL50 air bag-release accelerometer.

Cleanliness

MEMS are extremely sensitive to particulate matter at the back-end stages of manufacturing because of the tiny clearances of the mechanical structures. Special attention to cleanliness during the assembly and packaging steps for MEMS is needed to prevent the introduction of stray particles. Because ICs do not have similar particulate sensitivity, back-end steps can be done in a more relaxed manner. Most existing packaging facilities are not maintained at the level of processing cleanliness necessary for the high-yield packaging of MEMS. Manufacturers must either move MEMS packaging operations into a clean-room space or upgrade the cleanliness of their packaging laboratories.

Stiction

Interfacial adhesion is a major problem for movable MEMS devices (Chapter 2). Because final assembly and packaging processes take place after movable parts have been freed, these processes can have an effect on surface conditions and, hence, on stiction. Using dry- rather than wet-chemical processes in the latter phases reduces the likelihood of stiction.

Packaging Materials

The IC experience in packaging will provide an initial basis for the development of MEMS packaging. Because MEMS have applications in many demanding environments, however, some specialty materials will probably be necessary. In many cases, experience with hybrid sensing systems will provide guidelines to an enhanced materials-set for MEMS packaging. Adapting these materials to economical and compatible batch processes, however, presents a major challenge. Table 5-1 lists some characteristics of common IC chip packages.

Because of the interactive complexity of the overall IC-production process, changes in the IC infrastructure are not easily accepted, and process and materials modifications are made with great reluctance. MEMS production will require a much more flexible mind-set, although intensive research and development will be necessary for any modifications to existing procedures and materials. Frequently used IC materials are user qualified and available at much lower cost than new candidate materials, especially if the new materials are suitable only for customized MEMS applications. Because standard IC-package parts are typically made in batches of one hundred million or more, every effort should be made to use them whenever feasible. A very big payoff will accrue to designers who adapt these package parts to packaging demands for MEMS.

Stresses on Packaging

Differences in thermal-expansion coefficients between packaging materials and the MEMS chips are expected to cause temperature-variable stress patterns in packaged MEMS. These stresses can affect the electrical properties of devices (e.g., through piezoresistance) and can also change the mechanical properties affecting resonator frequencies and residual stresses in delicate parts like membranes. These problems must be alleviated for successful MEMS AP&T.

Fluid Environment

For most ICs, air or dry nitrogen is sealed in a hermetically sealed package. This milieu can be used for a fairly large class of MEMS as well. For some MEMS applications, however, an oil or viscous fluid may have to be incorporated into the package cavity (e.g., the seismic mass in accelerometers may have to be surrounded by fluid to damp shocks or prevent unwanted dynamic responses), or fluids may have to travel through the MEMS (e.g., Redwood Microsystems valves).

Vacuum Packaging

Some MEMS (e.g., resonant sensors) have to be packaged in an evacuated housing. The nature of the materials and sealing processes limits the kinds of packages that can be used, however. A particularly significant challenge for MEMS is developing a vacuum package that seals at lower than 50 mTorr, can be produced at reasonable cost (< \$1), and has a life of at least 10 years. Using solder-reflow packaging technology (e.g., from flip-chip processing) to form sealed, controlled-ambient packages at both the die and wafer level is one possibility. Other potential methods include the formation of a sealed cavity during the fabrication process itself. However, not all processes or device structures are directly compatible with this method, so new post-processing methods will have to be developed.

ASSEMBLY

If the microelectronic and micromechanical parts of MEMS can be produced using fully compatible processes, the difficult assembly of the two (or more) parts of the system will be avoided in many cases. Most reliability problems in systems can be traced to interfaces, and compatible processing would prevent the introduction of reliability problems during assembly. *Therefore, an important goal to enhance the development of MEMS is to enlarge the design space available to MEMS that can be compatibly batch processed.* Despite the advantage of fully integrating micromechanical and microelectronic parts in a single batch process, significant limitations would also be introduced (e.g., requiring the use

TABLE 5-1 Characteristics of Common IC Chip-Level Packages

Hermetic Package Types	Seal Material	Maximum Process Temperature	Issues	Figure
Welded package (can)	metal-to-glass	< 150°C	Material costs, accurate lead placement, diminishing user base	5–4
Side-brazed ceramic	solder	< 230°C	Requires gold, expensive (> $1/package)	5–5
Cerdip	glass	430°C	High seal temperature	1–5

of a silicon substrate would result in stringent processing and design revisions). But special needs and difficult processing challenges will almost certainly mean that mechanical and electrical processing for many future products will have to be separated. For this reason, techniques for electromechanical MEMS assembly are an important factor to consider.

A different class of assembly problems is introduced if micromechanical parts have to be assembled to form micromechanisms. Because of their tiny size, the mechanical assembly of micromechanisms is extremely difficult and is avoided as much as possible. In some technologies and for some devices, however, mechanical assembly may be unavoidable, and microassembly tools, some of them built using MEMS procedures, will have to be used.

Procedures that have been used to assemble micromechanical and microelectronic parts into MEMS thus far range from traditional hybrid-packaging methods to mating IC-fabricated electronics with micromechanical devices fabricated by a micromolding technique, such as LIGA. Most of the MEMS assembly available at this time is being used to integrate microsensing devices with electronics. Although three basic methods of electronic-MEMS integration are available (monolithic, flip-chip, and hybrid), only flip-chip and hybrid require the physical assembly of separate components.

Hybrid Assembly

Hybrid assembly is the most common method used today for assembling MEMS. Hybrid assembly methods range from simple systems, such as the Ford Microelectronics accelerometer (Figure 5-6), to the complex, multichip, multilevel assembly used in the dissolved-wafer process by a group at the University of Michigan (Figure 5-7). Hybrid assembly usually involves bonding two or more die to a single package, carrier, or substrate board, and then the interconnection of the separate chips by wire-bonding and/or package wiring. Hybrid assembly for MEMS can be done using equipment, materials, and testing methods common in the IC industry, including tools for die attachment, chip pinout, and heat removal, as well as for the measurement of signal-rise time, power-lead inductance, power-supply current, and interline coupling. The design of hybrid assembly also must consider factors like the wiring configuration for multiple chips and propagation delays as the signal is relayed between chips (NRC, 1990).

Using a flip-chip attachment (e.g., solder-bump technology) is a well established practice in the IC field, but the materials, processing, reliability, and manufacturing features required to make it viable for integrating separately fabricated micromechanical and microelectronic MEMS parts have only begun to be investigated (Markus, Koester, and Dhuler, 1994; Figure 5-8). Many issues need consideration and evaluation, such as the metallurgy of the solder attachment pads; the mechanical rigidity of the attached pair; the use of solder flux that requires liquid cleaning; the effect of the package flex on micromechanical properties and long-term stability of MEMS; the use of backfill material between the attached chip and the substrate; the presence of access holes to the "hidden" chip face; and the probability of survival in the environmental requirements.

Assembly of Micromechanical Parts

A special class of problems arises in cases where the subassembly of micromechanical parts is necessary to form mechanical elements. If at all possible, batch fabrication of in situ-assembled parts (as in surface-micromachined rotating micromotors) is preferable because of the scale of most micromechanisms in MEMS. If in-situ fabrication is not

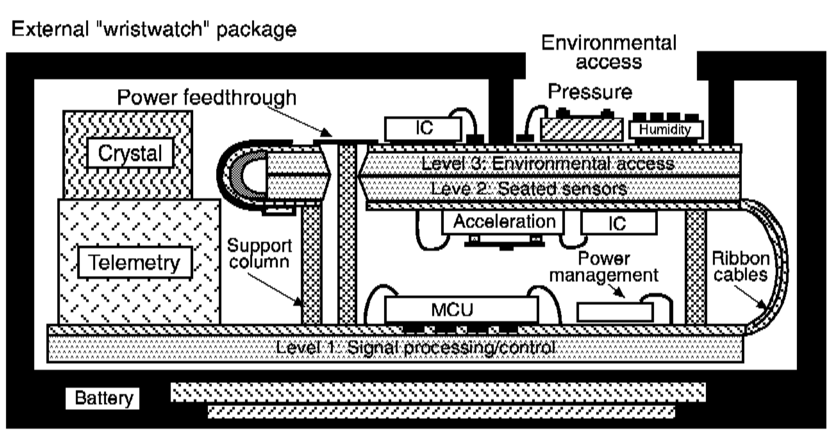

FIGURE 5-7 Detail of a multiplatform hybrid package showing feed-through, interconnect, and support features for an environmental monitoring cluster system. Source: Wise, 1995.

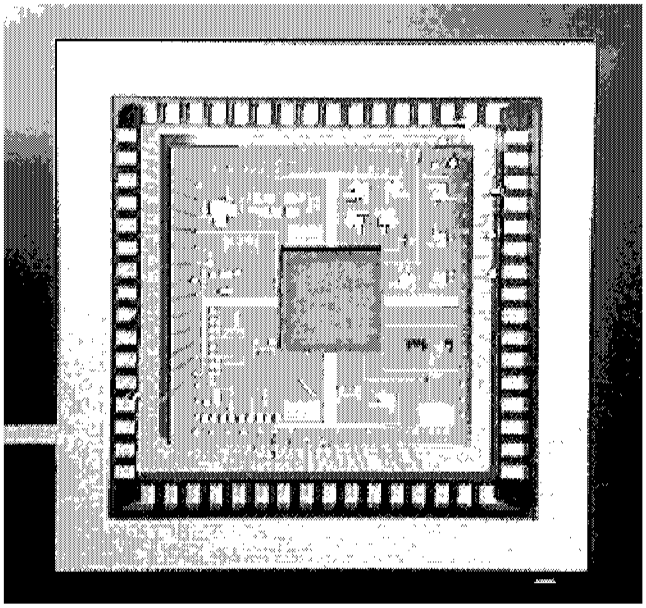

FIGURE 5-8 Flip-chip attachment of two die to form an integrated system. One die is an IC, the other a MEMS chip. Source: MCNC MEMS Technology Applications Center.

possible, methods of assembly will have to be devised. Ideas for microassembly operations can be obtained from present manufacturing experience in other industries that must gather and assemble very small pieces using specialized machinery (e.g., producers of computer disk drives). The scale of the MEMS devices will typically place new demands on assembly techniques, however, and research on ways to meet these demands will be necessary.

One inventive approach that can address a limited class of microassembly problems has been to make microparts with characteristic insertive geometries that fit in complementarily formed receptive geometric shapes (e.g., Yeh and Smith, 1994). Random mixing of the two systems results in assembly of the microparts similar to the joining-together of microbiological systems. This process has been used extensively throughout the milliscale assembly domain. A critical issue for this "batch assembly" approach is the effect of the liquid milieu in which the parts are randomized (usually by vibrating it), which can have devastating effects on yield for parts susceptible to stiction. If the microparts have to be manipulated one at a time, systems that can pick up, place, and assemble them must be developed. This approach to the microassembly problem is being addressed by a few research projects that use MEMS technologies to build microtweezers, micromanipulators, and pickups. (e.g., Oak Ridge National Laboratory, The Berkeley Sensor & Actuator Center). Given enough impetus, fully automated systems for subassembling micromechanisms will probably be developed. Some of the outstanding issues that need to be investigated are listed below:

- methods for array or row pick-and-place and for reorienting microparts via rotations about one or several axes
- maintaining tolerances in mating microparts
- controlling delicacy in interfacing the microtweezers and the potentially fragile micropart
- operating at speeds sufficient to qualify the microassembly process for reasonable use in a commercial process
- the degree to which procedures can be used with alignment pins, threaded assemblies, and other macroscopic design techniques
- maintaining sufficient precision of micropart production to permit the use of subassemblies—precision in MEMS-level micromechanical parts is typically significantly poorer than in macroscopic parts

Parts with large assembly tolerance can be assembled using robotic systems that can join a fluid port to a capillary with compression fittings or that can align a glass cap over a chip already bonded to a ceramic substrate. Technologies like LIGA are the impetus for the assembly of parts with very tight geometric tolerances. Recently, alignment-pin assembly fixtures have been used to assemble fluid microflow structures (Figure 3-3), stacked vertical magnetic actuators, and a series of magnetic linear actuators (Figure 5-9). For the microflow device, pin alignment holes were fabricated in the corners of the two mating pieces, and glass capillary pins were used to align and secure the two 500 μm thick pieces for subsequent thermal bonding. This form of pin-assembly has only been done manually, however.

Another assembly method for MEMS is physical bonding (fusion or anodic) of two or more wafers to assemble microparts into a micromechanical device (Roylance and Angell, 1979; Ko, Suminto, and Yeh, 1985; Peterson et al., 1988). Figure 5-10 shows the formation of a thermopneumatic microvalve using glass-to-silicon anodic wafer bonds. The silicon wafers are patterned and etched separately and then precisely aligned using equipment similar to equipment used in IC processing for lithography. The silicon wafers are then anodically bonded. This is basically a "sheet" method of assembly because an entire wafer surface of devices numbering into the thousands can be simultaneously assembled. The large-scale production of pressure sensors by Ford Motor Company is based on this technology. A related technique using other materials is employed by Hewlett-Packard to assemble their ink-jet printheads by positioning a thin nickel sheet over the closely spaced drivers formed on a silicon wafer.

Extending these wafer-bonding batch assembly methods to other microstructures will require additional work. Some of the challenges facing large-scale sheet assembly are the accuracy of placing parts both within a sheet and from sheet to sheet. Additional factors that complicate this method are

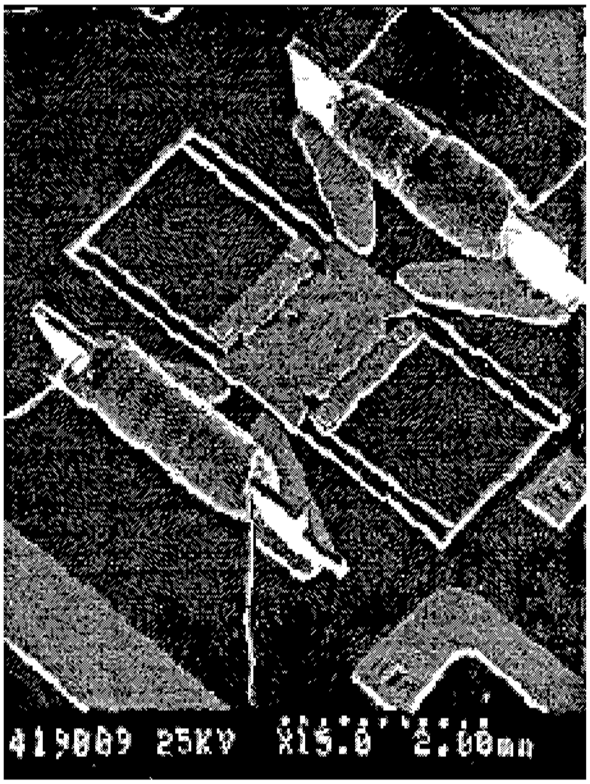

FIGURE 5-9 Assembled magnetic linear actuator. The coils are inserted into "spring fittings" and the shuttle/suspension assembly is inserted onto mounting pins located at the suspension anchor points. Source: Guckel et al., 1996b.

right-to-left or top-to-bottom shifts that occur when sheets, wafers, or assembly jigs translate through mirror, radial, or linear translations prior to assembly (e.g., face-to-face assembly aligns the right side of one sheet to the left side of the other). Once sheet-to-sheet (or wafer-to-wafer) assembly is completed, the separation of the individual die from the sheet can lead to additional complications, especially if the bonding pads formed on one wafer have been overlapped by the attached wafer. For biological applications, lower temperature bonding methods will have to be developed.

The assembly of optical fibers with other components has been done for some time using basic micromachining techniques. By inserting a fiber into a v-groove etched in a silicon wafer, the fiber can be aligned with other elements fabricated either in the wafer or on the wafer surface (Solgaard et al., 1995). With this method, however, the alignment between the fiber and other components can have errors of tens of microns, requiring further micromanipulation of either the fiber or the optical components. Work on addressing this issue through the use of movable microalignment structures (e.g., active alignment structures, moving mirrors, lenses, and fiber grips) is under way (Solgaard et al., 1995).

STANDARDS, TESTING, AND RELIABILITY

Functional and reliability testing are basic requirements for all manufacturing. Testing MEMS presents considerable challenges and typically requires not only electrical measurements but also environmental stimuli, such as fluid, shock, vibration, and temperature. Testing and characterization methods and structures suitable for the materials and domains of MEMS have yet to be developed. Standards organizations (e.g., American Society for Testing and Materials [ASTM] and National Institute of Standards and Technology [NIST]) and professional technical societies (e.g., Institute of Electrical and Electronics Engineers [IEEE]; American Institute of Mining, Metallurgical, and Petroleum Engineers [AIME]; and American Society of Mechanical Engineers [ASME]) will be invaluable for establishing standards, but significant interaction with the MEMS community needs to be instigated.

Manufacturers have traditionally qualified products using accelerated-aging tests carried out in extreme environments. The conditions of these tests need to be determined, and the standards for passing them must be established. A significant amount of effort has been expended to define and validate accelerated test methods for ICs and mechanical materials separately, but only some of this background work is directly applicable to MEMS. A challenge for MEMS is to evaluate the specifications that already exist and to incorporate or elaborate on them where appropriate. A suitable place to begin might be with military applications, where program-unique military specifications to ensure that systems or components will perform as expected (MIL-STD-490A) have already been established. The suitability of these specifications to MEMS in a limited, fairly well developed category (e.g., accelerometers) could be tested with the goal of evolving product-level testing to qualify MEMS for military use.

In the IC field, a great deal of important data about reliability has been contributed by academic researchers. Although academic research has not been focused on reliability in the MEMS area, this should be encouraged. Figure 5-11 shows typical processing specifications in the IC world, from die level testing to component/system-level testing. Better methods for testing and qualifying MEMS at all levels of the figure must be developed.

FAILURE ANALYSIS

Understanding and predicting failures is critical to the development of reliable products. Predicting failures is also essential for the establishment of specifications and standards. Understanding system-failure modes and processes requires failure analyses of systems. First, the definition of failure for a component or system must be established. A reasonable definition might be worded: "A failure occurs when there is a change in the performance of a component or

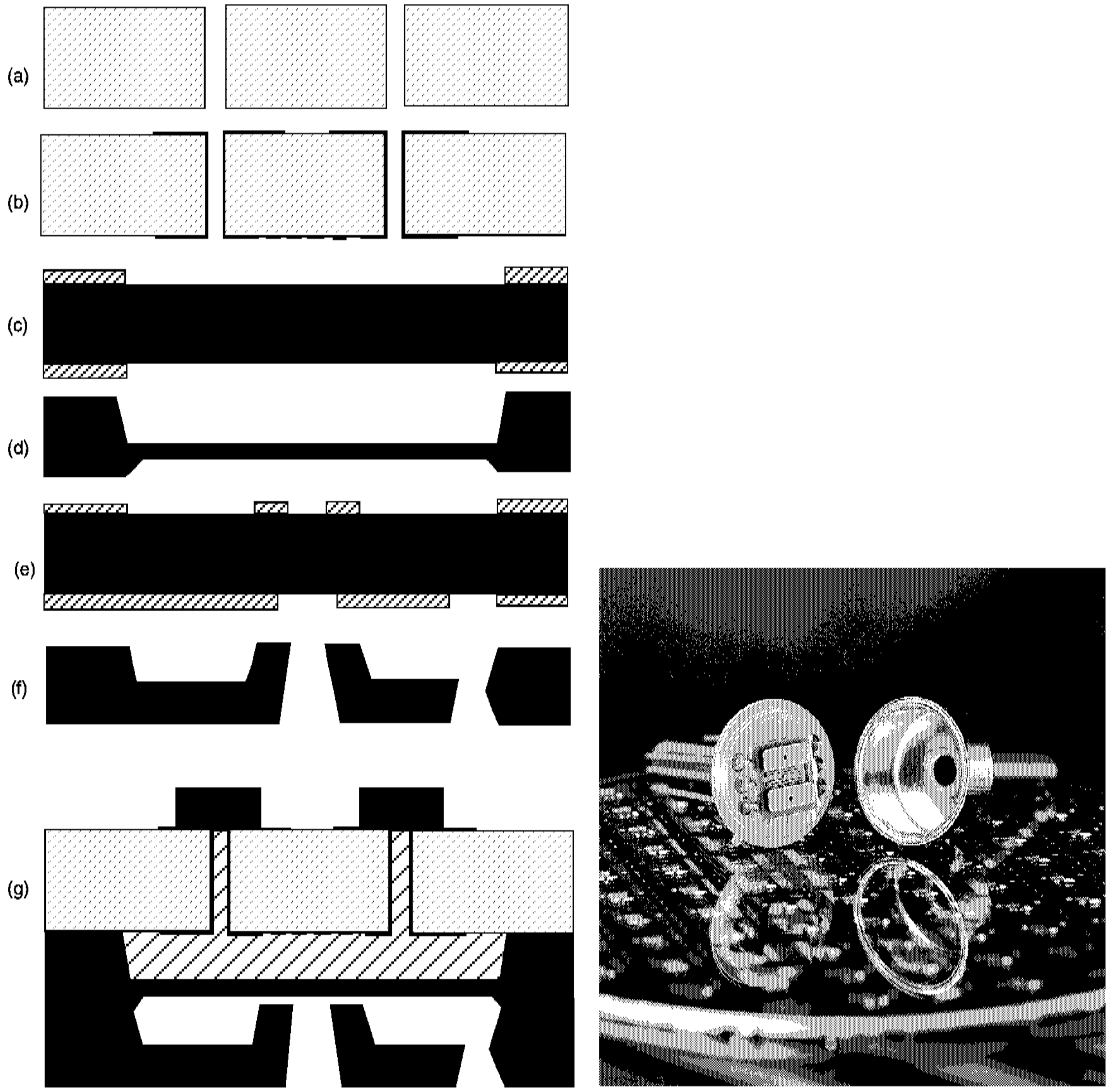

FIGURE 5-10 Packaged, normally-open microvalve (a 100 mm diameter silicon wafer provides a size reference) and process flow for fabrication of a normally-open, thermopneumatically-actuated microvalve: (a) holes are ultrasonically drilled in Pyrex wafer; (b) Pyrex wafer is metallized; (c) membrane wafer is defined lithographically (using gold, oxide, and photoresist masks); (d) membrane wafer is etched in KOH and masking materials are stripped; (e) orifice wafer is defined lithographically (using gold, oxide, and photoresist masks); (f) orifice wafer is etched in KOH and masking materials are stripped; (g) in the final steps, membrane and orifice wafers are fusion bonded, Pyrex is bonded to this sandwich anodically, and the thermopneumatic cavity is filled with liquid and sealed with silicon caps. Source: A. Henning, Redwood Microsystems.

system resulting in the inability to use the component or system as designed or intended." The goals of failure analysis are threefold: to identify the cause of the failure; to identify the critical features or parameters of the component or system; and to redesign the component or system based on the critical parameters to reduce the chances of failure. Failures in MEMS are caused by mechanical failure; electrical failure; electromechanical failure (e.g., failure of an actuated mechanical part); or interface failure (e.g., failure at a seal). Progress in MEMS will be significantly aided by collecting failure-analysis information in an accessible database. Industry does not generally share failure-analysis information for competitive reasons. In the IC world, however, there is a substantial open data bank of failure analyses because of the existence of foundries for many of the leading processes. MEMS is currently not yet defined by a common, standardized set of processes for commercial operation. The few standardized processes that do exist, at MCNC and Analog Devices through its multiproject runs, are contributing to a public data bank on failure modes in MEMS processing.

The data bank for MEMS should include: pertinent information on the component, system, and tests performed; basis

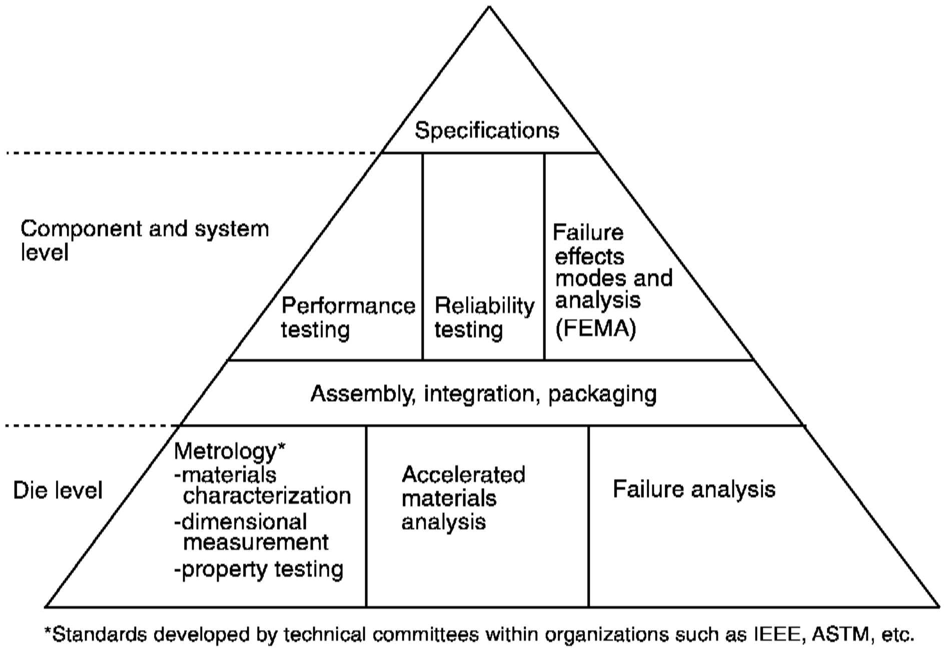

FIGURE 5-11 Specifications at all levels of testing. Source: Howard Last, Naval Surface Warfare Center.

of design for the component and system; "traditional" analysis tools (e.g., optical microscopy, circuit probing, and scanning electron microscopy) for identifying causes of failure; and appropriate methods for studying failure utilizing MEMS component or system-specific features (e.g., self-test capability). The following information is needed to perform a failure analysis: system identification (e.g., process lot); documentation of the fabrication process; documentation of performance- and life-testing for the same process lot (e.g., test conditions, numbers of cycles prior to failure, records of output signal and load as a function of time or number of cycles); and documentation of actual system testing and operational history.

SUMMARY

Although packaging, interfacing, and assembly have attracted less interest than the more glamorous areas of device and process development, these are critical final production steps and can easily represent up to 80 percent of the cost of a component. Along with testing, packaging, interfacing, and assembly represent critical stumbling blocks to the development and manufacture of commercial and military MEMS. Efforts to expand the currently small knowledge base in this field and to disseminate the results *aggressively* could have a significant positive effect. One of the most urgent needs is for generic packaging methods that would eliminate the need to invent or develop a new package for each new MEMS product. Obviously, there will never be a universal package because of the many application areas of MEMS, but it is possible to define a class of materials, procedures, and package designs that are suitable for the basic needs of MEMS in many areas (e.g., fluid handling, optical coupling, physical sensing). Generic packaging methodologies would also facilitate the evolution of packaging and testing equipment that can address specific MEMS requirements. Improvements in MEMS packaging and assembly will require better understanding of the interfaces between MEMS components and their operating environments, as well as better test methods and standards.

At the small scales at which MEMS are configured, material behavior is more influenced by surface-driven effects than by volume or bulk effects. If the interfaces act as electrical contacts (e.g., in MEMS microrelays), additional wear, corrosion, frictional effects, and contact forces are present. Surface-to-surface sticking (stiction) can also be important in surface-driven processes. The interfaces between a MEMS and its operating environment can also be troublesome and can demand considerable design and manufacturing effort. Signals admitted to the MEMS package can have electrical, thermal, inertial, fluid, chemical, optical, and possibly other origins. Outputs may include electrical, optical, mechanical, chemical, hydraulic, or magnetic signals, singly or in concert.

Standard test devices and methods are required to determine the mechanical properties of MEMS devices, to demonstrate the repeatability and reliability of mechanical devices, and to facilitate quality-control practices. Package-level testing is currently the most common way to measure MEMS performance, but the development of in-process wafer-level testing will be necessary for low-cost manufacturing. Wafer-level testing of MEMS presents special challenges that are often product dependent. Nevertheless, generic test-structures that indicate basic mechanical properties of MEMS materials at the wafer level should be developed and characterized. As more and more industries, universities, and other research groups enter the MEMS field, it is also becoming increasingly important to provide accepted standards that can be used for comparison.

Conclusion. Packaging, which has traditionally attracted little interest compared to device and process development, represents a critical stumbling block to the development and manufacture of commercial and military MEMS. The imbalance between the ease with which batch-fabricated MEMS can be produced and the difficulty and cost of packaging them limits the speed with which new MEMS can be introduced into the market. Alleviating the difficulties of packaging will require a better understanding of (1) the effects of internal friction, Coulomb friction, and wear at solid-solid interfaces and (2) the influence of interfaces on performance and reliability. Test and characterization methods and metrologies are general requirements for continued MEMS development and manufacturing advances. Finally, expanding the small knowledge base in this field and disseminating advances *aggressively* could have a profound influence on the rapid growth of MEMS.

Recommendation. Research and development should be pursued on (1) MEMS interfaces with operating environments, (2) MEMS packaging, and (3) MEMS assembly into useful engineering systems. The goal should be to define, insofar as possible, generic, modular approaches and methodologies and to extend batch-processing techniques into the various back-end steps of production.

Recommendation. Surface and interface studies should be pursued to address questions associated with contact forces, stiction, friction, corrosion, wear, lubrication, electrical effects, and microstructural interactions at solid, liquid, and gaseous interfaces. Engineering design and manufacturing solutions to these problems should also be pursued.

Recommendation. Standard test methods, characterization methods, and test devices that are suitable over the full range of materials and processes for MEMS should be developed and disseminated. Ideally, metrology structures will be physically small, simply designed, easily replicated, and conveniently and definitively interrogated. MEMS engineering standards should be similar to those already established for materials and devices in conventional sizes by organizations such as NIST, ASTM, and IEEE.

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APPENDICES

Appendix A

World Wide Web Sites on MEMS

Johnson, D., TiNi Alloy Company
www.sma-mems.com

University of Wisconsin
http://mems.engr.wisc.edu/moreinfo.html
http://mems.isi.edu/archives/otherWWWsites.html

European Information Clearinghouse on Microsystem Technology
http://mail.vdivde-it.de/ut/EMSTO

JTEC Panel Report on Microelectromechanical Systems in Japan
http://itri.loyola.edu/MEMS/TOC.htm

The Electronics Subcommittee
http://esc.sysplan.com/esc/index.html

Integrated Silicon Micro Optics in ETIS
http://guernsey.et.tudelft.nl/

DIMES Delft Institute of Mircoelectronics and Submicron Technology
http://muresh.et.tudelft.nl/dimes/index.html

JPL-CSMT Home Page
http://mishkin.jpl.nasa.gov/CSMT_PAGE

ISI MEMS Clearinghouse
http://mems.isi.edu/

Stanford Transducers Lab
http://transducers.stanford.edu/

MTL Research Area—Microelectromechanical Devices
http://goesser.mit.edu/MTL/Report94/MEMS/MEMS.html

Berkeley Sensor & Actuator Center
http://www-bsac.eecs.berkeley.edu/

MEMS Related Sites
http://cms.njit.edu/MEMSFolder/MEMSSites.html

JPL—MEMS on Internet
http://www.jpl.nasa.gov/quality/nasa/mems.htm#MEMS

DARPA MEMS
http://eto.sysplan.com/ETO/MEMS/

Analog Devices/MCNC iMEMS Server
http://imems.mcnc.org/

MCNC MEMS Home Page
http://mems.mcnc.org/

Appendix B

Biographical Sketches of Committee Members

RICHARD S. MULLER (chair) is professor emeritus of the Department of Electrical Engineering and Computer Sciences and co-director and co-founder of The Berkeley Sensor & Actuator Center of the University of California, Berkeley. He was awarded an M.E. from Stevens Institute of Technology and an M.S. and Ph.D. in physics and electrical engineering from the California Institute of Technology. He has been awarded NATO and Fulbright Research Fellowships at the Technical University, Munich, Germany; the Alexander von Humboldt Senior-Scientist Award; the University of California, Berkeley, Citation; the Stevens Institute of Technology Renaissance Award; the Transducers '95 Career Achievement Award; and the Institute of Electrical and Electronic Engineers (IEEE) 1998 Cledo Brunetti Award. Dr. Muller is a member of the National Academy of Engineering, the National Materials Advisory Board, the board of the Transducers Research Foundation, and the Advisory Committee for the Electron-Devices Society of IEEE, and he is editor-in-chief of the IEEE Journal of Microelectromechanical Systems. He is also a life fellow and distinguished lecturer of the IEEE, the chairman of the Sensors Advisory Board, and a trustee of the Stevens Institute of Technology. Dr. Muller is the author or co-author of more than 200 technical papers and conference presentations and the owner of 15 patents.

MICHAEL ALBIN is currently the director of science and technology at the Applied Biosystems Division of Perkin Elmer. He received a B.S. in chemistry from The Polytechnic Institute of New York and a Ph.D. in inorganic chemistry from The Pennsylvania State University. Following postdoctoral studies pertaining to the study of electron transfer mechanisms at California Institute of Technology, he has pursued an industrial career centered on the interface between chemistry and instrumentation in a number of fields. He joined Applied Biosystems in 1989 where he was involved in the development and commercialization of capillary electrophoresis systems and chemistries for three years. In the company's Science and Technology Group, he led the development and implementation of applications of microtechnology, including a three year, $15 million Advanced Technology Program (ATP) for the development of integrated, microgenetics systems. He is directly responsible for the technical assessment of advanced technologies and markets.

PHILLIP W. BARTH is a project engineer in the Chemical Systems Department of Hewlett-Packard Laboratories. He was awarded a B.S. from the University of Notre Dame and a M.S. and Ph.D. in electrical engineering from Stanford University. His research activities include the development of MEMS devices for ink-jet printers. He holds 11 issued patents pertaining to MEMS technologies.

SELDEN B. CRARY is research scientist in the Electrical Engineering and Computer Science Department at the University of Michigan, Ann Arbor, and president of Michigan Microsensor. He was awarded a Sc.B. from Brown University and a M.S. and Ph.D. in physics from the University of Washington. His research concerns the modeling of microsensors and microactuators and the computational optimal design of experiments.

DENICE D. DENTON is the dean of engineering and a professor in the Department of Electrical Engineering at the University of Washington. She received the B.S., M.S., and Ph.D. in electrical engineering from M.I.T. Her current interests include plasma deposition of polymers and the use of micromachining in solid state actuator design. Dr. Denton was co-director of the National Institute for Science Education in 1995–1996. She is a recipient of the NSF Presidential Young Investigator Award, the American Society of Engineering Education AT&T Foundation Teaching Award, the W.M. Keck Foundation Engineering Teaching Excellence Award, the American Society for Engineering Education (ASEE) George Westinghouse Award, and the IEEE Harriet B. Rigas Teaching Award.

KAREN W. MARKUS is director of the MEMS Technology Applications Center of MCNC and chairman of the board and executive director of the HI-MEMS Alliance, which is a First Round Technology Reinvestment Project (TRP). She was awarded a B.S. in electrical engineering from the University of Southern California.

PAUL MCWHORTER is the technical and programmatic leader of the Intelligent Micromachine Program at the Sandia National Laboratory, a program that uses Sandia's state-of-the-art 33,000 square foot microelectronics clean room to pursue a variety of MEMS technologies and components for the U.S. Department of Energy, industry, and government agencies. This program is one of the leading developers of MEMS technologies. Dr. McWhorter has a B.S. in electrical engineering from the University of Texas and a M.S. in electrical engineering from Stanford University. He has more than 50 technical publications and has received five IEEE best paper awards, two R&D 100 Awards, and Industry Week's "Top Technology of the Year" award.

ROBERT E. NEWNHAM is associate director of the Intercollege Materials Research Laboratory and Alcoa Professor of Solid State Science at The Pennsylvania State University. He was chairman of the Solid State Science Program for 18 years. Dr. Newnham is also affiliated with the Ceramic Science Section of the Materials Science and Engineering Department, where he teaches courses in crystal chemistry, crystal physics, and electroceramics. His research interests are structure–property relations, electroceramics, and composite materials for electronic applications. A member of the National Academy of Engineering, Dr. Newnham is the author of four books, more than 400 research papers, and was as co-editor of the Journal of the American Ceramic Society for a number of years. He has been an invited speaker at many meetings, especially those concerned with composite transducers and smart materials.

RICHARD S. PAYNE is the director of manufacturing for the Micromachined Products Division of Analog Devices, Incorporated, where the first dedicated wafer fabrication line for surface micromachined devices was built. He has worked in a variety of management positions at Analog Devices for 17 years and at Bell Laboratories for 10 years before that. He is a fellow of the IEEE and a recipient of the J.J. Ebers Award. He earned an A.B. in physics from Dartmouth College and a Ph.D. in physics from Yale University.