1 Introduction to MEMS

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1.1 Overview

Interest in the development of microelectromechanical systems (MEMS) has mushroomed during the past decade. In the most general sense, MEMS attempts to exploit and extend the fabrication techniques developed for the integrated circuit (IC) industry to add mechanical elements, such as beams, gears, diaphragms, and springs, to the electrical circuits to make integrated microsystems for perception and control of the physical world. MEMS devices are already being used in a number of commercial applications, including projection displays and the measurement of pressure and acceleration. New applications are emerging as the existing technology is applied to the miniaturization and integration of conventional devices.

This chapter starts with an overview of MEMS technology, followed by fabrication technologies, selected applications, commercial aspects, trends in MEMS technology, and journals and conferences (Table 1.1). The review covers both the potential and the limitations of MEMS technology.

Silicon anisotropic etching	pre-1950
Piezoresistive effect in silicon	1953
Semiconductor strain gauges	1957
Silicon pressure sensors	post-1960
Solid state transducers	post-1970
Microactuators	post-1980
Mechanisms and motors	198789
Microelectromechanical systems Microsystems Micromachines	post-1988

Table 1.1. Evolution of MEMS

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2 Introduction to MEMS

1.1.1 Historical Background

The transistor¹ was invented at Bell Telephone Laboratories on 23 December 1947. This invention, which led to a Nobel Prize awarded in 1948 to Schockley, Bardeen, and Brattain, initiated a fast-paced microelectronic technology. The transition from the original germanium (Ge) transistors with grown and alloyed junctions to silicon (Si) planar double-diffused devices took about 10 years. The IC concept was conceived by several groups, and included RCA's Monolithic Circuit Technique for hybrid circuits (1955). The first IC, shown in Fig. 1.1 was built by Jack Kilby of Texas Instruments in 1958, using Ge devices (a patent was issued to Kilby in 1959). A few months later, Robert Noyce of Fairchild Semiconductor announced the development of a planar Si IC. The complexity of ICs has doubled every 2 to 3 years since 1970. The minimum dimension of manufactured devices and ICs has decreased from 20 µm to the submicron levels of today. Currently, ultra-large-scale-integration (ULSI) enables the fabrication of more than 10 million transistors and capacitors on a typical chip. ULSI-based microprocessors and microcomputers have revolutionized communication, entertainment, health care, manufacturing, management, and many other aspects of our lives. Low-cost, high-performance electronic systems are now available to the public and have improved the quality of life in many ways. However, control and measurement systems, as well as the actual automation facilities used in IC fabrication, would be "deaf," "dumb," and "blind" without sensors to provide input from the surrounding environment. Similarly, without actuators, control systems would be powerless to carry out the desired functions. While IC technology (and more specifically, microfabrication) has provided high-speed, miniaturized, low-cost signal conditioning and signal-processing capabilities, conventional sensors and actuators (also referred to as transducers) are far behind in performance, size, and cost.

The success of Si as an electronic material in ULSI technology was due partly to its wide availability from silicon dioxide (SiO_2) (sand), resulting in potentially lower material costs relative to other semiconductors. Consequently, a significant effort was put into developing Si processing and characterization tools. Today, some of these tools are being utilized extensively to advance transducer technology. In this area, attention was first focused on microsensor (i.e., microfabricated sensor) development. Si microsensors initially addressed the measurement of physical variables, expanded to the measurement of chemical variables, and then progressed to biomedical applications. The first, and to date, the most successful microsensor, is the Si pressure sensor. The history of Si pressure sensors is representative of the evolution of microsensors.



Fig. 1.1. First integrated circuit consisting of one transistor, three resistors, and one capacitor. The IC was implemented on a sliver of germanium that was glued on a glass slide (Texas Instruments, Inc.).

1.1.1.1 Silicon Pressure Sensor Technology

In 1953, Dr. Charles S. Smith of Case Institute of Technology (now part of Case Western Reserve University [CWRU]), during a sabbatical leave at Bell Telephone Laboratories, studied the piezoresistivity of semiconductors and published the first paper on the piezoresistive effect in Ge and Si in 1954.² The piezoresistive effect is the change in the resistivity of certain materials due to applied mechanical strain. The measured piezoresistive coefficients indicated that the gauge factor of Ge and Si strain gauges could potentially be 10 to 20 times larger, and therefore much more sensitive than those based on metal films. As a result, discrete Si strain gauges were developed commercially in 1958 by Kulite Semiconductor Products, Honeywell, and Microsystems. Such Si strain gauges were integrated on a thin Si substrate as diffused resistors in 1961 by Kulite. The thin Si substrate was then mounted on a base to act as a diaphragm. In 1966, Honeywell developed a method to fabricate thin Si diaphragms by mechanically milling a cavity into an Si substrate. Isotropic Si etching was used to produce micromachined Si diaphragms in 1970, and anisotropic etching was introduced for this purpose in 1976. Both techniques were introduced by Kulite. Glass frits were introduced to bond the Si wafer (in which the pressure-sensitive diaphragms were fabricated) to a base wafer in the 1970s, allowing wafer-scale fabrication of pressure sensors. The first high-volume pressure sensor was marketed by National Semiconductor in 1974. This sensor included a temperature controller (in a hybrid package) for constant temperature operation. At this point, piezoresistive pressure-sensor technology had become a low-cost, batch-fabricated manufacturing technology. Further improvements of this technology have included the utilization of ion implantation for improved control of the piezoresistor fabrication. etch stops for improved control of the diaphragm thickness after the etch, deep Si-reactive ion etching for increased packing density, anodic bonding (electrostatic bonding), and more recently, Si-to-Si fusion bonding for improved packaging of the pressure sensors. Currently, Si pressure sensors are a billion-dollar industry and growing.³

The first monolithic integrated pressure sensor with digital (i.e., frequency) output was designed and tested in 1971 at CWRU.⁴ as part of a program addressing biomedical applications. Miniature Si diaphragms with a resistance bridge at the center of the diaphragm and sealed to the base wafer with a gold (Au)-tin (Sn) alloy were developed for implant and indwelling applications. During field evaluation, it was found that the packaging of the sensors determined their performance, and that piezoresistive sensors were very sensitive to interference, such as sideways forces, making them inaccurate for many biomedical applications. To achieve better sensitivity and stability, capacitive pressure sensors were first developed and demonstrated at Stanford University in 1977 and shortly afterward at CWRU. The first integrated monolithic capacitive pressure sensor was reported in 1980.⁵ In general, capacitive pressure sensors exhibit superior performance compared to traditional piezoresistive pressure sensors. However, the relatively complex design and implementation of signal-processing circuitry required for electronic readout initially limited the widespread availability of capacitive pressure sensors. During the last 15 years, various processing and transduction techniques have been used to develop new or improved Si pressure sensor designs. While such developments are ongoing, advanced piezoresistive Si pressure sensors still account for almost all of the Si pressure sensor market. During the same period, Si microsensor technology has matured substantially, and a variety of sensors have been developed for measuring position, velocity, acceleration, pressure, force, torque, flow, magnetic field, temperature, gas composition, humidity, pH, solution/body fluid ionic concentration, and biological gas/liquid/molecular concentrations. Some of these sensors have been commercialized.

1.1.1.2 Micromachining

Development of Si microsensors often required the fabrication of micromechanical parts (e.g., a diaphragm in the case of the pressure sensor and a suspension beam for many accelerometers). These micromechanical parts were fabricated by selectively etching areas of the Si substrate away to leave behind the desired geometries. Hence, the term "micromachining" came into use around 1982 to designate the mechanical purpose of the fabrication processes that were used to form these micromechanical parts. Isotropic etching of Si was developed in the early 1960s for transistor fabrication. Anisotropic etching of Si was reported in 1967 by Finne and Klein⁶ and in 1973 by Price.⁷ Various etch-stop techniques were subsequently developed to provide further process flexibility. Together, these techniques have been used for fashioning micromechanical parts from Si materials, and they also form the basis of the "bulk" micromachining processing techniques. Bulk micromachining designates the point that the bulk of the Si substrate is etched away to leave behind the desired micromechanical elements.

While bulk micromachining has been a powerful technique for the fabrication of micromechanical elements, ever-increasing needs for flexibility in device design and performance improvement have motivated the development of new concepts and techniques for micromachining. For example, the application of the sacrificial layer technique (first demonstrated by Nathanson and Wickstrom in 1965⁸) to micromachining in 1985 gave birth to the concept of "surface" micromachining.⁹ Surface micromachining designates the point that the Si substrate is primarily used as a mechanical support upon which the micromechanical elements are fabricated. More recently, the introduction of Si fusion bonding and deep reactive ion etching, as well as high-aspect-ratio lithography and plating processes, have expanded the capabilities of micromachining technology.

Prior to 1987, Si micromachining had been used to fabricate a variety of micromechanical structures, such as thin Si diaphragms, beams, and other suspended structures, in single-crystal Si or in films deposited on an Si substrate. These micromechanical structures were generally limited in motion to small deformations and were physically attached to the substrate. Such elastic components could be used as flexible joints, but their overall usefulness in the design of "mechanisms" was limited. "Mechanism" as used here is a means for transmitting, controlling, or constraining relative movement and refers to a collection of rigid bodies connected by joints. During 1987 to 1988, a turning point in the field was reached when, for the first time, techniques for integrated fabrication of mechanisms on Si were demonstrated.^{10,11} It was then possible to fabricate mechanical parts that could execute unrestrained motion in at least one degree of freedom (e.g., gears, gear trains, linkages). Shortly thereafter, this technology enabled the development of electrostatic micromotors^{12,13} and motivated the development of other types of microactuators, such as valves, pumps, switches, tweezers, and lateral resonant devices.

1.1.1.3 MEMS

Recent progress in microactuators is transforming the conventional field of solid-state transducers into what has become known as MEMS. The term "MEMS" was coined around 1987, when a series of three workshops on microdynamics and MEMS was held in July 1987 in Salt Lake City, Utah; in November 1987 in Hyannis, Massachusetts; and in January 1988 in Princeton, New Jersey. These workshops ushered in a new era of microdevices. Equivalent terms for MEMS include "microsystems," which is preferred in Europe, and "micromachines," which is favored in Japan. MEMS is application driven and technology limited, and has emerged as an interdisciplinary field that involves many areas of science and engineering.

Miniaturization of mechanical systems promises unique opportunities for new directions in the progress of science and technology. Micromechanical devices and systems are inherently smaller,

lighter, faster, and usually more precise than their macroscopic counterparts. However, the development of micromechanical systems requires appropriate fabrication technologies that enable the following features in general systems:

- · Definition of small geometries
- Precise dimensional control
- · Design flexibility
- Interfacing with control electronics
- · Repeatability, reliability, and high yield
- Low cost per device

1.2 Fabrication Technologies

The three characteristic features of MEMS fabrication technologies are miniaturization, multiplicity, and microelectronics. Miniaturization is clearly an important part of MEMS, since materials and components that are relatively small and light enable compact and quick-response devices. Multiplicity refers to the batch fabrication inherent in semiconductor processing. Consequently, it is feasible to fabricate thousands or millions of components as easily and concurrently as one component, thereby ensuring low unit component cost. Furthermore, multiplicity provides flexibility in solving mechanical problems by enabling the possibility of a distributed approach through use of (coupled) arrays of micromechanical devices. Finally, microelectronics provides the intelligence to MEMS and allows the monolithic merger of sensors, actuators, and logic to build closed-loop feedback components and systems.

Clearly, the successful miniaturization and multiplicity of traditional electronics systems would not have been possible without IC fabrication technology. It is therefore natural that the IC fabrication technology, or microfabrication, has so far been the primary enabling technology for the development of MEMS. Microfabrication provides a powerful tool for batch processing and miniaturization of mechanical systems into a dimensional domain not accessible by conventional (machining) techniques. Furthermore, microfabrication provides an opportunity for integration of mechanical systems with electronics to develop high-performance, closed-loop-controlled MEMS. Integrated fabrication techniques, which are made possible by IC fabrication technology, eliminate the need for discrete component assembly, which is not practical for the fabrication of MEMS. Hence, dimensional control, including component size and intercomponent clearance, is limited only by the processing technology.

Even though miniaturization of mechanical systems is directly compared to that of electronics, two important points should be noted. First, not all mechanical systems will benefit from miniaturization. More likely, microfabricated sensors and actuators that enable performance improvement will be integrated into conventional macroscopic mechanical systems. Miniaturization and the application of microtransducers for monitoring and control is justified when the performanceto-cost ratio is improved. Second, current IC-based fabrication technologies are inherently planar, not allowing full flexibility for three-dimensional (3D) design. A mature technology for micromechanical systems will require complementary fabrication techniques that provide3D design capabilities.

1.2.1 IC Fabrication

Any discussion of MEMS first requires a basic understanding of IC fabrication technology. The major steps in this technology include film growth, doping, lithography, etching, dicing, and packaging (see Fig. 1.2). Devices are usually fabricated on Si substrates, which are grown in boules, sliced into wafers, and polished. Thin films are grown on these substrates and are used to build active components, passive components, and interconnections between circuits. These films



Fig. 1.2. Major processing steps in integrated circuit fabrication.

include: (1) epitaxial Si, (2) SiO₂, (3) silicon nitride (Si₃N₄), (4) polycrystalline Si (polysilicon), and (5) metal films. To modify electrical or mechanical properties, films are doped with impurities by thermal diffusion or ion implantation. Lithography is used to transfer a pattern from a mask to a film via a photosensitive chemical called a photoresist. The film is then selectively etched away, leaving the desired pattern in the film. This cycle is repeated until fabrication is complete. The wafers are then probed for yield, diced into chips, and packaged as final devices. Because there is a market for high-quality, inexpensive Si wafers (namely, microelectronics), most MEMS fabrication facilities focus on thin-film growth, doping, lithography, and etching processes.

1.2.1.1 Film Growth

The growth of SiO₂ by the thermal oxidation of Si is the fundamental film growth process. In IC fabrication, oxidation is used for passivating the Si surface, masking diffusion and ion implantation layers, growing dielectric films, and providing an interface between Si and other materials. In MEMS, SiO₂ films are also used as etch masks and sacrificial layers, which will be discussed later. Although Si exposed to air at room temperature will grow a native oxide (about 20 Å thick), thicker oxide films (0.5–1.5 μ m) can be grown at elevated temperatures in a mixture of hydrogen (H₂) and oxygen (O₂) gases. The rate of oxide growth is dependent on the growth temperature, the oxygen partial pressure, and the crystal orientation of the Si substrate. However, for a fixed temperature, oxide thickness increases with time in parabolic fashion.

To deposit SiO₂ films on substrates other than Si, a process known as chemical vapor deposition (CVD) is used. In this process, the chemical components of the film are supplied to the reactor as a mixture of gases. The substrate is heated to a temperature that induces a pyrochemical reaction and film formation. Such depositions are performed at atmospheric pressure (AP) or low pressure (LP). In most instances, the process is ideal for batch coating. Growth rates are much higher in APCVD systems, while films are deposited with excellent thickness uniformity in LPCVD systems. CVD is also used to deposit thick (>1.5 μ m) oxide films or when the substrate cannot be simply oxidized thermally. In addition to SiO₂, metals, polysilicon, Si₃N₄, and many other films can be deposited by CVD.

Epitaxial growth is a special class of CVD. Epitaxy is defined as growth of a single crystal film upon a single crystal substrate. If the composition of the film is the same as that of the substrate, the process is called homoepitaxy. However, if the film composition differs from that of the substrate, the process is called heteroepitaxy. Many compound semiconductors, such as gallium arsenide (GaAs) and silicon carbide (SiC), can be grown heteroepitaxially on Si, while doped Si layers are homoepitaxial.

Many films are not thermally stable at temperatures commonly used in conventional CVD. To reduce deposition temperatures so that existing films will not be adversely affected, CVD pyrochemical reactions are combined with a radio-frequency (RF) plasma in a process known as plasma-enhanced CVD (PECVD). PECVD results in films with good step coverage and low pinhole density. However, PECVD films generally suffer from significant hydrogen incorporation and lower mass density, degrading the electrical and mechanical properties of a material.

Metal films can be deposited by vacuum evaporation, sputtering, CVD, and plating, and are most commonly used for interconnections, ohmic contacts, and rectifying metal-semiconductor contacts. Vacuum evaporation is used to deposit single-element conductors, resistors, and dielectrics. Alloys can also be deposited by this method, but the process is complicated by the widely varying evaporation rates of different metals. Resistive and electron beam heating are the two most common heat sources. Compound materials and refractive metals can be deposited by sputtering a cathode target with positive ions from an inert gas discharge. Introduction of noninert gases into the ambient during sputtering is called reactive sputtering and is used to deposit compound films such as titanium nickel (TiNi).

1.2.1.2 Doping

In many instances, it is desirable to modulate the properties of a device layer by introducing a low and controllable level of impurity atoms into the layer. This process is called doping and is accomplished by either thermal diffusion or ion implantation. Thermal diffusion is performed by heating the wafers in a high-temperature furnace and passing a dopant-containing carrier gas across the wafer. The diffusion process occurs in two stages: predeposition and drive-in. During

predeposition, dopant atoms are transported from the source onto the wafer surface and are diffused into the near-surface region. The sources can be gaseous (e.g., diborane $[B_2H_6]$) or solid (e.g., boron nitride [BN]), depending on the dopant. During drive-in, the temperature is increased, and the dopant diffuses into the wafer to the desired depth and concentration. Ion implantation introduces dopants below the wafer surface by bombardment with an energetic beam of dopant ions. Because the energy loss of these ions in Si is well known, precise control of the dose and depth of dopants is possible. The crystal lattice is damaged during this process, but the damage can often be reduced by subjecting the wafer to a high-temperature, postimplant anneal.

1.2.1.3 Lithography

Lithography is the technique by which the pattern on a mask is transferred to a film or substrate surface via a radiation-sensitive material. The radiation may be optical, x-ray, electron beam, or ion beam. For optical exposure, the radiation-sensitive material is more commonly called "photoresist", and the process is called "photolithography." Photolithography consists of two key steps: (1) pattern generation and (2) pattern transfer. Pattern generation begins with mask design and layout using computer-aided design (CAD) software, from which a mask set is manufactured. A typical mask consists of a glass plate coated with a patterned chromium (Cr) film. Pattern transfer involves: (1) dehydration and priming of the surface, (2) photoresist coating of the wafer, (3) "soft bake" of the photoresist, (4) exposure of the photoresist through the mask, (5) chemical development of the photoresist, (6) wafer inspection, and (7) postdevelopment bake or "hard bake." After hard bake, the mask pattern has been completely transferred to the photoresist.

1.2.1.4 Etching

Following hard bake, the desired pattern is transferred from the photoresist to the underlying film or wafer by a process known as etching. Etching is defined as the selective removal of unwanted regions of a film or substrate and is used to delineate patterns, remove surface damage, clean the surface, and fabricate 3D structures. Semiconductors, metals, and insulators can all be etched with the appropriate etchant. The two main categories of etching are wet-chemical and dry-etching. As the name implies, wet-chemical etching involves the use of liquid reactants to etch the desired material. However, tighter governmental regulations on safety and waste, coupled with the trend toward smaller device features, have led to an increasing emphasis on dry etching. There are various types of dry-etch processes, ranging from physical sputtering and ion-beam milling to chemical-plasma etching. Reactive ion etching, the most common dry-etch technique, uses a plasma of reactant gases to etch the wafer, and thus is performed at low pressure in a vacuum chamber. Well-characterized wet-chemical and dry-etch recipes for most semiconductor processing materials can be found in the literature and will not be detailed here.

In order to fabricate structures, etching is used in conjunction with photolithographically patterned etch masks. The effectiveness of an etchant depends on its selectivity, that is, its ability to effectively etch the exposed layer without significantly etching the masking layer. Since most etch masks are not completely impervious to etchants, mask thicknesses depend on the selectivity of the etchant and the total etch time. Suitable etch-mask materials for many dry- and wet-chemical etchants include SiO_2 , Si_3N_4 , and hard-baked photoresist.

1.2.2 Bulk Micromachining and Wafer Bonding

Bulk micromachining was developed between 1970 and 1980, as an extension of IC technology, for fabrication of 3D structures.¹⁴ Bulk micromachining of Si uses wet- and dry-etching techniques in conjunction with etch masks and etch stops to sculpt micromechanical devices from the

Si substrate. There are two key capabilities that make bulk micromachining of Si a viable technology. First, anisotropic etchants of Si, such as ethylene-diamine and pyrocatechol (EDP), potassium hydroxide (KOH), and hydrazine (N_2H_4), are available that preferentially etch single crystal Si along given crystal planes. Second, etch masks and etch-stop techniques are available that can be used in conjunction with Si anisotropic etchants to selectively prevent regions of Si from being etched. As a result, it is possible to fabricate microstructures in an Si substrate by appropriately combining etch masks and etch-stop patterns with anisotropic etchants.

Good etch masks for typical anisotropic etchants are provided by SiO_2 , Si_3N_4 , and some metallic thin films such as Cr and Au. These etch masks protect areas of Si from etching and define the initial geometry of the region to be etched. Alternatively, etch stops can be used to define the microstructure thickness. Two techniques for etch stopping have been widely used in conjunction with anisotropic etching in Si. One technique that uses heavily boron (B)-doped Si, called "p+ etch stop," is effective in practically stopping the etch. Another technique, called "pn junction," stops the etch when one side of a reverse-biased junction diode is etched away.

Anisotropic wet etchants of Si, such as KOH, are able to etch Si <100> and <110> crystal planes significantly faster than the <111> crystal planes. In a <100> Si substrate, etching proceeds along the (100) planes but is practically stopped along the <111> planes. Since the <111> crystal planes make a 54.7-deg angle with the <100> planes, slanted walls result, as shown in Fig. 1.3. Because of the slanted <111> planes, the size of the etch-mask opening determines the final size of the etched hole or cavity. If the etch mask openings are rectangular and the sides are aligned with the [110] direction, practically no undercutting of the etch-mask feature takes place. However, significant undercutting below the mask may occur in convex corners (corners with angles greater than 180 deg), where the etch-mask openings. Under these circumstances, the undercutting continues until it is limited by the <111> planes. Undercutting can be used to fabricate suspended microstructures. Figure 1.4 shows a bulk micromachined Si cantilever fabricated by undercutting the beam's convex corners-defined by an etch stop-from the front side of the wafer.

A drawback of wet anisotropic etching is that the microstructure geometry is defined by the internal crystalline structure of the substrate. Consequently, fabricating multiple, interconnected micromechanical structures of free-form geometry is often difficult or impossible. Two additional processing technologies have extended the range of traditional bulk micromachining technology: deep anisotropic dry etching and wafer bonding. Deep anisotropic dry etching of Si can be achieved using reactive gas plasmas, which will etch exposed Si vertically. Recent improvements in this technology allow the patterning and etching of high-aspect-ratio (e.g., 20:1), anisotropic, randomly shaped features into a single crystal Si wafer, with only photoresist as an etch mask.¹⁵ As shown in Fig. 1.5, etch depths of a few hundred microns into an Si wafer are possible while maintaining smooth, vertical sidewall profiles. The other technology, wafer bonding, permits an Si substrate to be attached to another substrate, typically Si or glass. Electrostatic (or anodic) bonding of Si to glass substrates is performed under application of pressure and high voltage (400-1000 V), while Si fusion bonding (SFB) is the bonding of two Si wafers at high temperatures (near 1000°C), in an O2 or N2 ambient. By combining anisotropic etching and wafer bonding techniques, bulk micromachining technology can be used to construct 3D complex microstructures such as microvalves and micropumps. Figure 1.6 presents a microvalve that is fabricated by anisotropic etching and bonding of four Si wafers. In addition to dry etching and wafer bonding, the capabilities of bulk micromachining are further enhanced by laser processing techniques (Chapter 5) applied to microstructures up to 1-mm thick with 20:1 aspect ratios.



Fig. 1.3. Bulk micromachined features realized by anisotropic etching of silicon. (a) Bottom plan view of etched wafer with cavities, diaphragms, and holes; (b) top plan view of an anisotropically etched wafer showing the fabrication of a cantilever beam using etch stop layer; (c) cross section, AA', showing the hole, diaphragm, and cavity of (a); and (d) cross section, BB', showing the cantilever beam of (b).



Fig. 1.4.Bulk micromachined cantilever fabricated by p+ etch stop and anisotropic etching.



Fig. 1.5. Complex shapes patterned using deep reactive ion etching (DRIE).

1.2.3 Surface Micromachining

Surface micromachining relies on encasing specific structural parts of a device in layers of a sacrificial material during the fabrication process. The sacrificial material is then dissolved in a chemical etchant that does not attack the structural parts. In surface micromachining, the substrate wafer is used primarily as a mechanical support on which multiple, alternating layers of structural and sacrificial material are deposited and patterned to realize micromechanical structures. Surface micromachining enables the fabrication of complex, multicomponent, integrated micromechanical structures that would be impossible with traditional bulk micromachining.



Fig. 1.6. Schematic cross section of a microvalve fabricated by bulk micromachining and wafer bonding. The TiNi shape memory film is thermally actuated to open and close the microvalve (H. Kahn, Case Western Reserve University).

A typical surface micromachining process, shown in Fig. 1.7, begins with the deposition of a sacrificial layer, which is then patterned to create openings to the underlying substrate. Next, the structural layer is deposited and patterned into the desired geometry. Finally, the structural components are released by removal of the underlying and surrounding sacrificial material. The structural components are attached to the underlying substrate at the anchor regions.

Surface micromachining is a versatile technology for three key reasons. First, the patterning of the structural and sacrificial layers is typically accomplished by etching processes that are insensitive to the crystalline structure of the films, thereby providing flexibility for planar free-form designs. Second, surface micromachining enables integrated multilevel structures using multiple layers of structural and sacrificial material. Third, there is no express restriction on the structural-sacrificial material system, as long as the compatibility between the structural and sacrificial materials is maintained. Therefore, different application-specific structural layers can be used in conjunction with suitable sacrificial layers.

Polysilicon surface micromachining using polysilicon as the structural material and SiO_2 as the sacrificial material has been the most widely used surface micromachining technique. When electrical isolation of the substrate and/or the structural components is required, Si_3N_4 is used as



Fig. 1.7. Cross-sectional schematic demonstration of surface micromachining. (a) Sacrificial layer deposition, (b) definition of the anchor and bushing regions, (c) structural layer patterning, and (d) free-standing microstructure after release.

an insulator. In this process, hydrofluoric acid (HF) is used to dissolve the sacrificial oxide during release. Figure 1.8 presents a surface-micromachined shear-stress microsensor fabricated using a single structural layer of polysilicon. Another commercially used surface micromachining technique utilizes aluminum (Al) and photoresist as the structural and sacrificial layers, respectively. In this case, the release of the structural Al layer is accomplished by removing the sacrificial photoresist using a plasma etch. A number of other material systems have also been investigated as structural/sacrificial layers for surface micromachining: Al/polyimide, Si₃N₄/polysilicon, and Si₃N₄/SiO₂. The maximum thickness of structural layers in traditional surface micromachining is limited to 10 μ m or less because of residual stresses in films. Excessive residual stress can lead to mechanical failure during fabrication. Furthermore, there are process limitations due to slow film deposition rates in traditional methods such as CVD, sputtering, and evaporation. Faster deposition rates can be realized for films that can be grown using pulsed laser deposition (PLD) or plating techniques.

1.2.4 Micromolding

Micromolding refers to fabrication of microstructures using molds to define the deposition of the structural layer. After the structural layer deposition, the final microfabricated components are realized when the mold is dissolved in a chemical etchant that does not attack the structural material. Micromolding is an additive process, in that the structural material is deposited only in those



Fig. 1.8. SEM of a shear-stress microsensor fabricated by surface micromachining using a single structural layer of polysilicon.

areas constituting the microdevice structure. In contrast, bulk and surface micromachining are examples of subtractive micromachining processes, which feature blanket deposition of the structural material followed by etching to realize the final device geometry.

A widely known micromolding process is lithographie, galvanoformung, und abformung (LIGA). This German acronym means lithography, electroplating, and molding. The process can be used for the manufacture of high-aspect-ratio, 3D microstructures in a wide variety of materials (e.g., metals, polymers, ceramics, and glasses).^{16,17} As shown in Fig. 1.9, high-intensity, lowdivergence, hard x rays are used as the exposure source for the lithography. These x rays are usually produced by a synchrotron radiation source. Polymethylmethacrylate (PMMA) is used as the x-ray resist. Thicknesses of several hundreds of microns and aspect ratios of more than 100 have been achieved. A characteristic x-ray wavelength of 0.2 nm allows the transfer of a pattern from a high-contrast x-ray mask into a resist layer with a thickness of up to 1000 µm so that a resist relief may be generated with an extremely high depth-to-width ratio. The openings in the patterned resist can be preferentially plated with metal, yielding a highly accurate complementary replica of the original resist pattern. The mold is then dissolved away to leave behind plated structures with sidewalls that are vertical and smooth. It is also possible to use the plated metal structures as an injection mold for plastic resins. After curing, the metallic mold is removed, leaving behind microreplicas of the original pattern. By combining LIGA with the use of a sacrificial layer, it is also possible to realize free-standing micromechanical components.¹⁸

A chief drawback of the LIGA process is the need for a short-wavelength collimated x-ray source like a synchrotron. Consequently, LIGA-like processes using conventional exposure sources are being developed. Photoresists with high transparency and high viscosity can be used to achieve a single-coating mold thickness in the range of 15 to 500 μ m.^{19–21} Thicker photoresist layers may be realized by multiple coatings. In such photoresist layers, standard ultraviolet (UV) photolithography is used to achieve mold features with aspect ratios as high as 11:1.

Photosensitive polyimides are also used for fabricating plating molds.²² The photolithography process is similar to conventional photolithography, except that polyimide works as a negative resist. In this process, about 10- μ m-wide lines can be delineated in several tens of microns-thick



Fig. 1.9. Outline of the micromolding process using LIGA technology. (a) Photoresist patterning, (b) electroplating of metal, (c) resist removal, and (d) molded plastic components.

resist. A maximum aspect ratio of 8:1 can be achieved, but depends on the geometry of the mask layout. Polyimide is a very stable material and does not have to be cured to act as a plating mold, but it is also limited in terms of the thickness and the aspect ratio.

All methods stated above make use of lithography techniques to make a mold, but dry etching of polyimides to form high-aspect-ratio molds has also been reported.²³ In these methods, some modifications of traditional reactive ion etching (RIE) systems are necessary to achieve high-aspect ratios. For example, dry etching of fluorinated polyimides with a titanium (Ti) mask has been used for deep etching with high-aspect ratios, excellent mask selectivity, and smooth side-walls.^{23,24}

Using micromolding processes, it is possible to realize high-aspect-ratio metallic microstructures, which are especially attractive for certain applications, including reflective surfaces for optical components, low resistivity contacts for relays, magnetic metals for electromagnetic actuators/sensors, and microfabricated coils. Additionally, the larger thickness of high-aspect-ratio structures provides for greater stiffness perpendicular to the substrate, as well as for increased force/torque in electrostatic actuators. Plated nickel (Ni), copper (Cu), or alloys that contain at least one of these metals are the structural metals commonly used; Cr, SiO₂, polyimide, photoresist, and Ti have been often used as the sacrificial material.

1.3 MEMS Components

The miniaturization, multiplicity, and microelectronics characteristics of MEMS technology make it especially attractive to realize small-size, low-cost, high-performance systems integrated on one chip. Microfabricated pressure sensors have dominated the MEMS application market for the last two decades. With advances in IC technology and corresponding progress in MEMS fabrication processes in the last decade, additional integrated microsensor and microactuator systems are now being commercialized, and even more applications are expected to benefit. In this section, we present examples of some commercially available MEMS components selected on the basis of fabrication technique and system complexity. First, pressure sensors are presented as an example of a MEMS device fabricated using bulk micromachining, followed by integrated accelerometers that are fabricated by surface micromachining. Next, the suitability of MEMS technology in complex, array-type application systems is demonstrated using the example of a digital micromirror device (DMD). Finally, the potential of MEMS components in aerospace applications is discussed, and some promising devices are listed.

1.3.1 Pressure Sensors

MEMS technology has been utilized to realize a wide variety of differential, gauge, and absolute pressure microsensors based on different transduction principles. Typically, the sensing element consists of a flexible diaphragm that deforms due to a pressure differential across it. The extent of the diaphragm deformation is converted to a representative electrical signal, which appears at the sensor output.

Figure 1.10 shows a manifold absolute pressure (MAP) sensor for automotive engine control, designed to sense absolute air pressure within the intake manifold (manufactured by Motorola, Schaumburg, Illinois). This measurement can be used to compute the amount of fuel required for each cylinder in the engine. The microfabricated sensor integrates on-chip, bipolar op-amp circuitry and thin-film resistor networks to provide a high output signal and temperature compensation.

The sensor die/chip consists of a thin Si diaphragm fabricated by bulk micromachining. Prior to the micromachining, piezoresistors are patterned across the edges of the diaphragm region using standard IC processing techniques. After etching of the substrate to create the diaphragm, the sensor die is bonded to a glass substrate to realize a sealed vacuum cavity underneath the diaphragm. Finally, the die is mounted on a package such that the top side of the diaphragm is exposed to the environment through a port. A gel coat isolates the sensor die from the environment while allowing the pressure signal to be transmitted to the Si diaphragm. The ambient pressure forces the diaphragm to deform downward, resulting in a change of resistance of the piezoresistors. This resistance change is measured using on-chip electronics; a corresponding voltage signal appears at the output pin of the sensor package.

1.3.2 Accelerometers

Acceleration sensors are relatively newer applications of MEMS technology. Typically, the sensing element consists of an inertial mass suspended by compliant springs. Under acceleration, a force acts on the inertial mass, causing it to deviate from its zero-acceleration position, until the restoring force from the springs balances the acceleration force. The magnitude of the inertialmass deflection is converted to a representative electrical signal, which appears at the sensor output.

Figure 1.11 shows a monolithic accelerometer (manufactured by Analog Devices, Inc., Norwood, Massachusetts), the ADXL-50, fabricated by surface micromachining and BiCMOS (a



Fig. 1.10. Commercially available absolute pressure sensor. (a) Sensor package; (b) cross-sectional schematic (Motorola, Inc.).²⁵

combination of bipolar junction transistor [BJT] and complementary metal-oxide semiconductor [CMOS]) processes. The inertial mass consists of a series of 150- μ m-long fingerlike beams connected to a central trunk beam, all suspended 2 μ m above the substrate by tether beams. The ADXL-50 uses a capacitive measurement method: the deflection of the inertial mass changes the capacitance between the finger beams and the adjacent cantilever beams. The sensor structure is surrounded by supporting electronics, which transduce the capacitance changes due to acceleration into a voltage, with appropriate signal conditioning.

The analog output voltage is directly proportional to acceleration, and is fully scaled, referenced, and temperature compensated, resulting in high accuracy and linearity over a wide temperature range. Internal circuitry implements a forced-balance control loop that improves linearity and bandwidth. Internal self-test circuitry can electrostatically deflect the sensor beam upon demand, to verify device functionality.



Fig. 1.11. Surface micromachined integrated accelerometer. (a) Chip overview, (b) close-up of sensor structure showing central trunk beam and fingers (Analog Devices, Inc.).

1.3.3 DMDs

The DMD (manufactured by Texas Instruments, Inc., Dallas, Texas) is a microchip consisting of a superstructure array of Al micromirrors functionally located over CMOS memory cells. The DMD digital light switch moves between the "on" and "off" states to create and reflect digital gray-scale images from its surface when light is applied. These digitally created images are transferred through appropriate optics and filters to create projected and/or digitally printed images.

The Al micromirror superstructure is realized by surface micromachining, while the underlying memory cells are fabricated using standard CMOS processes. The mirrors are hermetically sealed beneath nonreflecting glass to prevent contamination-induced failure. Figure 1.12 shows the details of the DMD microchip. Each mirror is 16 μ m square with a 1- μ m space between mirrors on all sides. The number of mirrors in use on a single chip can range from 307,200 to 1.3+ million (with one mirror per pixel).

To achieve digital operation, the DMD micromirrors are designed to be bistable. In the "on" mode, the mirrors deflect +10 deg, while in the "off" position, the mirrors rest at -10 deg. When a given CMOS memory cell is loaded with a digital 1, electrostatic forces switch the corresponding mirror "on" to reflect light into the aperture of an imaging lens. Memory cells loaded with a digital 0 cause the mirror to switch "off," and to direct incident light away from the imaging lens. In conjunction with appropriate optics, a color wheel, and electronic control circuitry, the DMD can be used to display high-quality projection images.

1.3.4 Sensors and Actuators in Aerospace Applications

Sensors are required in a variety of aerospace instrumentation, including fuel measurement and monitoring, landing gear, ice protection, and navigation. In small, private aircraft, the instrumentation is simple and may consist only of an altimeter to register height, an indicator to register airspeed, and a compass. The most modern airplanes and manned spacecraft, in contrast, have fully automated "glass cockpits," in which a tremendous array of sensor information is continually presented on the aircraft's height, attitude, heading, speed, cabin pressure and temperature, route, fuel quantity and consumption, and on the condition of the engines and the hydraulic, electrical, and electronic systems. Aerospace vehicles are also provided with inertial guidance systems for automatic navigation from point to point, with continuous updating for changing weather conditions, beneficial winds, or other situations. This array of instrumentation is supplemented by vastly improved meteorological forecasts, which reduce the hazard from weather, including such difficult-to-predict elements as wind shear and microburst.

Attitude and direction of aerospace vehicles are handled by flight controls that actuate elevators, ailerons, and rudders through a system of cables or rods. In sophisticated modern aircraft, there is no direct mechanical linkage between the attitude and direction devices used by the pilot and the actual controls used to achieve the changes in attitude and direction; instead, these controls are actuated by electric motors. The catch phrase for this arrangement is "fly by wire." In addition, in some large and fast aircraft, controls are boosted by hydraulically or electrically actuated systems. In both the fly-by-wire and boosted controls, the feel of the control reaction is fed back to the pilot by simulated means.

The use of MEMS devices in aerospace systems is expected to be highly application specific and would typically aim to reduce size, weight, and power consumption at the component level. Changes in both commercial and military markets for fixed-wing and rotor-wing aircraft demand increased performance with less weight. The cost advantage and electronic integration capabilities of MEMS enables the feasibility of distributed measurement and actuation. These features would be based on flexible location of smart transducers and decreased reliance on pneumatics, which would, in turn, lead to more accurate measurements, reduced vulnerability through redundancy, fewer moisture drain traps, and considerable weight savings.

In addition to conventional aircraft, evolution of MEMS technology should lead to the development of micro, unmanned aerial vehicles (μ UAVs). These small flight vehicles would perform as aerial robots whose mobility could be used to deploy micropayloads to a remote site or to otherwise hazardous locations.



Fig. 1.12. DMD microchip. (a) Portion of the micromirror array, (b) exploded view of a single (16-µm-edge length) micromirror element (Texas Instruments, Inc.).

Figure 1.13 shows a commercially available pressure measurement instrument, the micro, air data transducer (manufactured by BF Goodrich Company, Richfield, Ohio), which measures static and total pressures using micromachined Si-based sensors. This instrument is only 25% of the size and weight of its conventional non-MEMS-based counterparts, and exhibits a 0.02% full-scale pressure accuracy. Applications include primary accuracy air data for flight control, cockpit display, navigation, and fire control.



Fig. 1.13. Photograph of the Micro-Air Data Transducer, a commercially available MEMS-based sensor for use in aircraft (BF Goodrich Co.).

A number of other MEMS devices have been developed for aerospace applications. Although most of these devices are still at the research stage, their eventual integration into aerospace systems will revolutionize flight safety and performance. One of the devices that has been realized, the miniaturized ice detector, uses bulk micromachining and wafer bonding techniques. The detector is shown in Fig. 1.14.²⁶ The sensing element is 2 mm square and can detect ice films as low as 0.1 mm thick. Table 1.2 presents examples of MEMS devices with potential aerospace applications.



Fig. 1.14.Microfabricated ice detection sensor.

22 Introduction to MEMS

Device Application	Fabrication Method	Transduction Principle	Organization	
Shear Stress Sensor	Surface micromachining	Capacitive detection	Case Western Reserve University, Cleveland, OH	
	Bulk micromachining	Optical detection	Massachusetts Institute of Technology (MIT), Cambridge, MA	
Accelerometer	Integrated surface micromachining	Capacifive detection	Analog Devices, Norwood, MA	
	Surface micromachining	Capacitive detection	Motorola, Phoenix, AZ	
	Bulk micromachining	Piezoresistive detection	Endevco, Capistrano, CA	
Pressure Sensor	Bulk micromachining	Piezoresistive detection	Lucas Novasensor, Sunnyvale, CA	
	Bulk micromachining	Piezoresistive detection	Motorola, Phoenix, AZ	
Angular Rate Gyroscope	Surface micromachining. micromolding	Capacitive detection	Draper Labs, Cambridge, MA	
	Surface micromachining	Capacitive sensor	University of California, Berkeley	
Drag Reduction	Bulk micromachining, micromolding	Magnetic flap actuator	University of California, Los Angeles	
Fuel Atomization	Bulk micromachining	Precision nozzle	CWRU	
Screech Control	Bulk micromachining	Electrostatic microactuator	University of Michigan, Ann Arbor	
Communication Fil- ters and Oscillators	Surface micromachining	Electrostatic resonators	University of Michigan	
Microrelays	Surface micromachining, micromolding	Electrostatic actuator	CWRU	
	Surface micromachining	Electrostatic actuator	Hughes Research Labs. Malibu, CA	
	Surface micromachining, micromolding	Magnetic actuator	Georgia Institute of Technology, Atlanta	
Optical Scanners	Surface micromachining	Electrostatic micromotor	CWRU	
	Surface micromachining	Electrostatic resonator	UC, Berkeley	

Table 1.2. Examples of MEMS	with Potential ir	Aerospace App	plications
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1.4 Commercial Applications

The potential of MEMS technology promises to revolutionize our present-day life-styles as much as the computer has. In addition to completely new applications enabled by MEMS technology, existing applications will likely be replaced by miniaturized, low-cost, high-performance, "smart" MEMS technology. The potential for cost-effective and high-performance systems has attracted attention from both government and industry alike. The substantial up-front investment often required for successful, large-volume commercialization of MEMS is likely to limit the initial involvement to larger companies in the IC industry. These companies can leverage their existing capital investment in semiconductor processing equipment toward the development of MEMS components for large-volume applications.

1.4.1 MEMS Market

Currently, MEMS markets and demand are overwhelmingly in the commercial sector, with the automobile industry being the main consumer for micromachined pressure sensors and accelerometers. Market studies predict that the value of MEMS products will increase to between \$12 and \$14 billion by the year 2000 (see Fig. 1.15) and that no one product and/or application area will dominate the MEMS industry for the foreseeable future.²⁷

The MEMS market for sensors will continue to grow, particularly for sensors with integrated signal processing, self-calibration, and self-test. However, a substantial portion of the MEMS market will be in non-sensing, actuator-enabled applications, such as scanners, fuel-injection systems, and mass data storage devices. Furthermore, because MEMS products will be embedded in larger, non-MEMS systems (e.g., printers, automobiles, biomedical diagnostics), the products will enable new and improved systems, with projected market value approaching \$100 billion in the year 2000.²⁷

1.4.2 MEMS Industry Structure

A number of companies are already marketing MEMS devices and systems for commercial use. These companies include a broad range of manufacturers of sensors, industrial and residential control systems, electronic components, automotive and aerospace electronics, analytic instruments, and biomedical products. Examples of such companies include Goodyear, Honeywell, Lucas Novasensor, Motorola, Hewlett-Packard, Analog Devices, Texas Instruments, Siemens, and Hitachi. In addition, many small, emerging businesses have also been formed to commercialize MEMS components.

With the advent of commercialization of MEMS, many technology requirements being identified are capabilities beneficial to the industry as a whole, but too costly to develop by any one company. MEMS manufacturing is heavily dependent on microelectronics manufacturing, and at the moment, there is no MEMS-equipment and material-supplier infrastructure separate from that of microelectronics equipment and material industry. While advanced MEMS device designs, systems concepts, and fabrication processes will continue to be important, advances in MEMS manufacturing resources will pace future development, commercialization, and use of MEMS.

Unlike microelectronics, where a few types of fabrication processes satisfy most microelectronics manufacturing requirements, MEMS, given their intimate and varied interaction with the physical world, exhibit a greater variety of device designs and associated manufacturing resources. For example, the thin-film structures created using surface micromachining techniques, while well-suited for the relatively small force encountered in inertial measurement devices, are not adequate for MEMS fluid valves and regulators. Similarly, the thicker structures created using a combination of wafer etching and bonding, while well-suited to the higher forces and motions



Fig. 1.15. Projected worldwide MEMS market through the year 2000.²⁷ (a) Growth of worldwide market in MEMS components and devices: (b) non-sensor market segments in the year 2000, which will constitute at least 50% of the market for MEMS products.

in fluid valves and regulators, consume too much power to be used for the fabrication of microoptomechanical aligners and displays. There is not likely to be a MEMS equivalent of a CMOS process like that in microelectronics that will satisfy the majority of MEMS device fabrication needs.²⁷ MEMS design is strongly coupled to packaging requirements, which are dictated by the application environment.

The different MEMS fabrication processes and equipment will often be developed by larger firms with a particular and large commercial market as the target. Typically, the firm developing the manufacturing resources needs to focus on the production of products for those one or two markets driving applications. But in most cases, once the manufacturing resource is developed, numerous products for smaller markets could be addressed with the same manufacturing resources. No single one of these smaller markets would have justified the development of the fabrication process. For the firms that have developed the manufacturing resource, addressing small and fragmented markets is not currently economically justifiable, given the market diversity and

the embryonic state of electronic design aids. Most of these specialized markets will only be attractive and economically justifiable to smaller businesses that, however, do not have (nor would they want to duplicate) the manufacturing resources.

1.5 Trends in MEMS Technology

MEMS technology is extending and increasing the ability to both perceive and control the environment by merging the capabilities of sensors and actuators with information systems. Future MEMS applications will be driven by processes that enable greater functionality through higher levels of electronic-mechanical integration and greater numbers of mechanical components working either alone or together to enable a complex action. These process developments, in turn, will be paced by investments in the development of new materials, device and systems design, fabrication techniques, packaging/assembly methods, and test and characterization tools.

1.5.1 Design and Simulation

MEMS is more demanding of design aids than microelectronics production. Most industrial designs of physical sensors today are based on detailed finite-element modeling of the mechanical microstructures using software available for conventional mechanics.

MEMS requires new drawing and layout tools to generate the patterns that will be used to add or remove material during processing. In addition, MEMS requires a number of different modeling tools, including simulators for mechanical deformation, electrostatic fields, mechanical forces, electromagnetic fields, material properties, and electronic devices. MEMS also needs the connective algorithms to reconcile and blend results from all the different simulators.

As devices become more complex and multiple simulators are involved, the complexity of both the simulations and the coupling increases considerably. Traditional modeling techniques become impractical and may even fail. Radically new approaches to modeling and simulation for the many physical effects and different MEMS functions have to be developed.

1.5.2 Materials Issues

An extensive, well-documented materials database that meets the requirements of MEMS development is essential for continuing progress in the field. Many of the new material property simulators will need new models and data to relate process parameters to material properties relevant for MEMS design.

The accuracy of the existing microelectronic device simulators is built on historic and huge amounts of material and device measurements, coupled to carefully controlled process conditions. By knowing the relationship between processing conditions and the resulting material parameters, microelectronics manufacturers can control material properties, and hence, device yields. Circuit designers are typically interested in those material properties that relate to the electronic function of the devices, such as doping levels and dielectric constants.

The material needs of the MEMS field are well recognized but are at a preliminary stage. In addition to single-crystal Si, polysilicon, Si_3N_4 , and SiO_2 , other materials are being explored for MEMS. Interesting examples include SiC, shape memory alloy (SMA) metals, permalloy, and high-temperature superconductive materials. All these materials possess certain unique properties that, when combined with MEMS technology, make them attractive for certain applications.

A thorough understanding of the material properties of existing MEMS materials is just as important as the development of new materials for MEMS. There are very few reliable measurements of material properties (for example, modulus, residual stress, or reflectivity) relevant to the production of MEMS. The goal of studying the material properties in MEMS, and in thin films generally, is to develop models that relate process parameters to the film microstructure, as well as to the corresponding mechanical, electrical, optical, and thermal properties. Chapter 3 elaborates on the material properties and the required tests to enable a valid database.

1.5.3 Integration with Microelectronics

Future MEMS products will demand yet higher levels of electrical-mechanical integration and more intimate interaction with the physical world. The full potential of MEMS technology will only be realized when microelectronics is merged with the electromechanical components. Integrated microelectronics provides the intelligence to MEMS and allows closed-loop feedback systems, localized signal conditioning, and control of massively parallel actuator arrays.²⁷

Although MEMS fabrication uses many of the materials and processes of semiconductor fabrication, there are important distinctions between the two technologies. The most significant distinctions are in the process recipes (the number, sequence, and type of deposition, removal, and patterning steps used to fabricate devices) and in the end stages of production (bonding of wafers, freeing of parts designed to move, packaging, and test). The fundamental challenge of using semiconductor processes for MEMS fabrication is not so much in the type of processes and materials used, but more in the way those processes and materials are used.

MEMS will need the development of operating conditions on standard semiconductor equipment suited and optimized to the requirements of MEMS. For other processing steps unique to MEMS, the development of new manufacturing equipment and associated processes will be required. Table 1.3 lists some of the specialized process equipment that is required to enhance the manufacturability of MEMS.

1.6 Journals and Conferences

Before 1980, the literature on solid-state sensors and actuators was scattered in various application fields such as electronic devices, automobiles, instrumentation, materials, physics, and analytical chemistry. The journal *Sensors and Actuators* was first published in 1980 to provide a forum for publication of papers in the field. Another journal, *Sensors and Materials*, issued by MYU Japan, began publication in 1989. Rapid advances in device design, fabrication, materials,

Fabrication Technology	Process Equipment
Surface micromachining	Release and drying systems to realize free-standing microstructures
Bulk micromachining	Dry etching systems to produce deep, 2D free-form geometries with vertical sidewalls in substrates
	Anisotropic wet etching systems with protection for wafer front sides during etching
	Bonding and aligning systems to join wafers and perform photolithography on the stacked substrates
Micromolding	Batch-plating systems to create metal molds in LIGA process
	Plastic injection molding systems to create components from metal molds

testing, packaging, and applications, as well as the rapid expansion of the field, have brought about many journals, symposia, and conferences to report on the progress being made. There are now many publications dealing with sensors and actuators, including trade journals and regional publications. In the MEMS area, the *Journal of Microelectromechanical Systems* is a quarterly (started in 1992) published jointly by the Institute of Electrical and Electronics Engineers (IEEE) and the American Society of Mechanical Engineers (ASME), the *Journal of Micromechanics and Microengineering* is a quarterly (started in 1991) published by the American Institute of Physics, while *Microsystem Technology* is a quarterly (started in 1995) published by Springer-Verlag.

The International Conference on Solid State Sensors and Actuators, also referred to as the Transducers Conference, was established in 1981. The conference sponsors biannual meetings (during odd years), rotating between the United States, Japan, and Europe. The latest meeting concluded in Chicago in June 1997 (called Transducers '97). The conference also publishes a technical digest. In addition, some of the papers presented at the conference are published in special issues of *Sensors and Actuators*.

Regional conferences on sensors, actuators, and MEMS are held in both Japan and Europe. In the United States, a workshop on solid-state sensors and actuators has been held at Hilton Head, North Carolina, during even years. Technical digests from these workshops are also published. Another series of international conferences, entitled IEEE Workshop on Micro Electro Mechanical Systems, started in 1987 and has met annually between 1989 and 1998. Each of the conferences has published a proceedings volume. Finally, a number of conferences in other fields (e.g., International Electron Device Meeting, Device Research Conference/Materials Research Conference, The Electrochemical Society Meeting, and many SPIE conferences) hold sessions on microsensors, microactuators, and MEMS.

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