35 Microfabrication Technologies

CHAPTER CONTENTS

An important trend in engineering design and manufacturing is the growth in the number of products and/or components of products whose features sizes are measured in microns (1 μm = 10^{-3} mm = 10^{-6} m). Several terms have been applied to these miniaturized items. The term ***microelectromechanical systems*** (MEMS) emphasizes the miniaturization of systems consisting of both electronic and mechanical components. The word ***micromachines*** is sometimes used for these devices. ***Microsystem technology*** (MST) is a more general term that refers to the products (not necessarily limited to electromechanical products) as well as the fabrication technologies to produce them. A related term is ***nanotechnology***, which refers to even smaller products whose dimensions are measured in nanometers (1 nm = 10^{-3} μm = 10^{-9} m). Figure 35.1 indicates the relative sizes and other factors associated with these terms. Microfabrication techniques are discussed in the current chapter and nanofabrication in Chapter 36.

35.1 Microsystem Products

Designing products that are smaller and comprised of even smaller parts and subassemblies means less material usage, lower power requirements, greater functionality per unit space, and accessibility to regions that are forbidden to larger products. In most cases, smaller products should mean lower prices because less material is used; however, the price of a given product is influenced by the costs of research, development, and production, and how these costs can be spread over the number of units sold. The economies of scale that result in lower-priced products have not yet fully been realized in microsystems technology, except for a limited number of cases that are examined in this section.

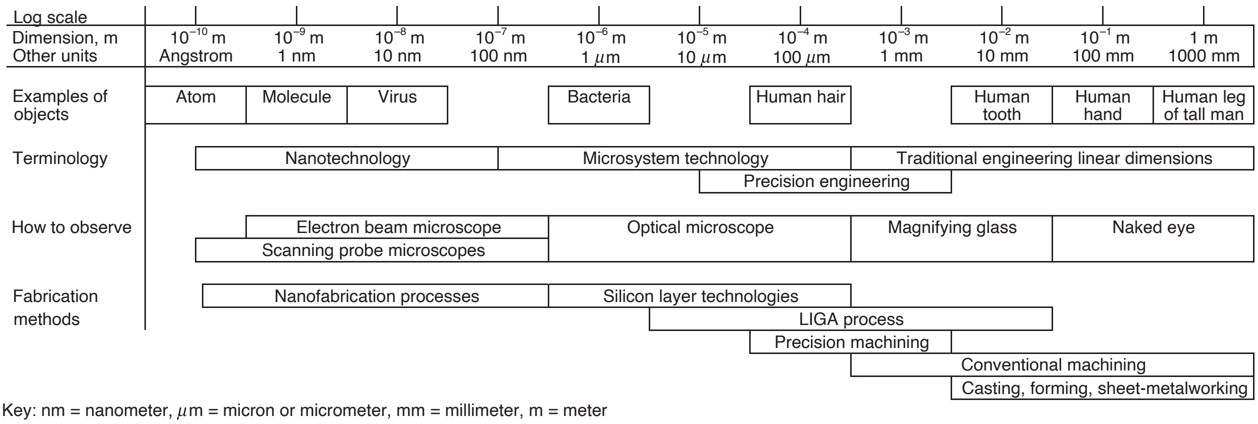

FIGURE 35.1 Terminology and relative sizes for microsystems and related technologies.

35.1.1 TYPES OF MICROSYSTEM DEVICES

Microsystem products can be classified by type of device (e.g., sensor, actuator) or by application area (e.g., medical, automotive). The device categories are as follows [1]:

- ***Microsensors***. A sensor is a device that detects or measures some physical phenomenon such as heat or pressure. It includes a transducer that converts one form of physical variable into another form (e.g., a piezoelectric device converts mechanical force into electrical current) plus the physical packaging and external connections. Most microsensors are fabricated on a silicon substrate using the same processing technologies as those used for integrated circuits (Chapter 33). Microscopic-sized sensors have been developed for measuring force, pressure, position, speed, acceleration, temperature, flow, and a variety of optical, chemical, environmental, and biological variables. The term ***hybrid microsensor*** is often used when the sensing element (transducer) is combined with electronic components in the same device.
- ***Microactuators***. Like a sensor, an actuator converts a physical variable of one type into another type, but the converted variable usually involves some mechanical action (e.g., a piezoelectric device oscillating in response to an alternating electrical field). An actuator causes a change in position or the application of force. Examples of microactuators include valves, positioners, switches, pumps, and rotational and linear motors [1]. Figure 35.2 shows a microscopic ratchet mechanism fabricated of silicon.
- ***Microstructures and microcomponents***. These terms are used to denote a microsized part that is not a sensor or actuator. Examples of microstructures and microcomponents include microscopic gears, lenses, mirrors, nozzles, and beams. These items must be combined with other components (microscopic or otherwise) to provide a useful function. Figure 35.3 shows a microscopic gear alongside a human hair for comparison.
- ***Microsystems and micro-instruments***. These terms denote the integration of several of the preceding components together with the appropriate electronics

FIGURE 35.2
Microscopic ratchet mechanism fabricated of silicon (Photo courtesy of Paul McWhorter).

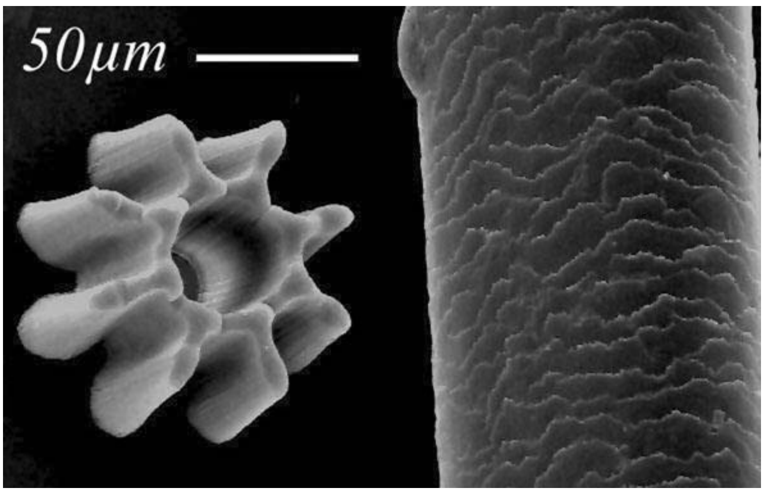

FIGURE 35.3
A microscopic gear and a human hair. The image was made using a scanning electron microscope. The gear is high-density polyethylene molded by a process similar to the LIGA process (Section 35.2.2) except that the mold cavity was fabricated using a focused ion beam. (Photo courtesy of M. Ali, International Islamic University Malaysia.)

package into a miniature system or instrument. Microsystems and micro-instruments tend to be very application specific; for example, microlasers, optical chemical analyzers, and microspectrometers. The economics of manufacturing these kinds of systems have tended to make commercialization difficult.

35.1.2 MICROSYSTEM APPLICATIONS

The preceding microdevices and systems have been applied in a wide variety of fields. There are many problem areas that can be approached best using very small devices. Some important examples are the following:

Ink-Jet Printing Heads This is currently one of the largest applications of MST, because a typical ink-jet printer uses up several cartridges each year. The operation of an ink-jet printing head is depicted in Figure 35.4. An array of resistance heating elements is located above a corresponding array of nozzles. Ink is supplied by a reservoir and flows between the heaters and nozzles. Each heating element can be independently activated under microprocessor control in microseconds. When activated by a pulse of current, the liquid ink immediately beneath the heater boils to form a vapor bubble, forcing ink to be expelled through the nozzle opening. The ink hits the paper and dries almost immediately to form a dot that is part of an alphanumeric character or other image. Meanwhile, the vapor bubble collapses, drawing more ink from the reservoir to replenish the supply. Today's ink-jet printers possess resolutions of 1200 dots per inch (dpi), which converts to a nozzle separation of only about 21 μm, certainly in the microsystem range.

Thin-Film Magnetic Heads Read-write heads are key components in magnetic storage devices. These heads were previously manufactured from horseshoe magnets that were manually wound with insulated copper wire. Because the reading and writing of magnetic media with higher-bit densities are limited by the size of the read-write head, hand-wound horseshoe magnets were a limitation on the technological trend toward greater storage densities. Development of thin-film magnetic heads at IBM Corporation was an important breakthrough in digital storage technology as well as a significant success story for microfabrication technologies. Thin-film read-write heads are produced annually in hundreds of millions of units, with a market of several billions of dollars per year.

A simplified sketch of the read-write head is presented in Figure 35.5, showing its MST parts. The copper conductor coils are fabricated by electroplating copper through

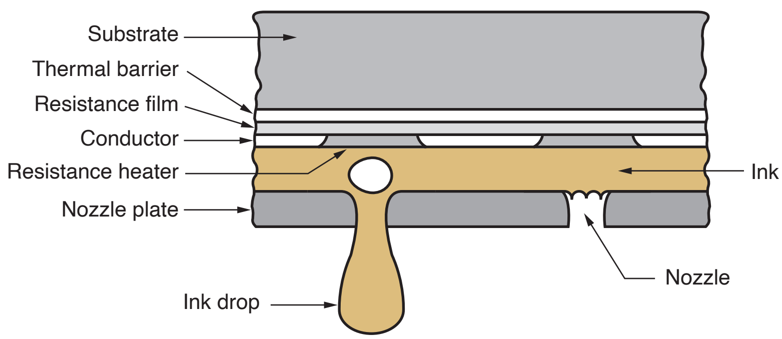

FIGURE 35.4 Diagram of an ink-jet printing head.

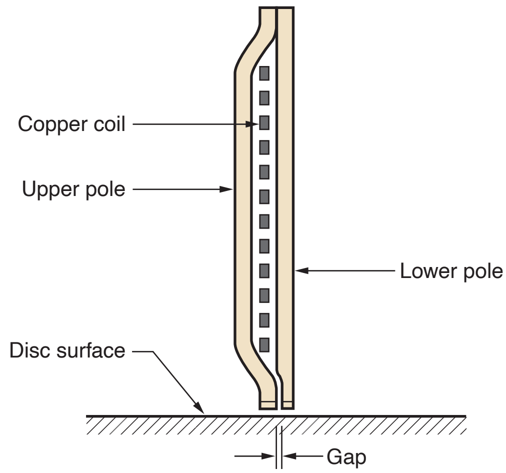

FIGURE 35.5 Thin-film magnetic read-write head (simplified).

a resist mold. The cross section of the coil is about 2 to 3 μm on a side. The thin-film cover, only a few μm thick, is made of nickel–iron alloy. The miniature size of the read-write head has permitted the significant increases in bit densities of magnetic storage media. The small sizes are made possible by microfabrication technologies.

Compact Discs Compact discs (CDs) and digital versatile discs (DVDs)[1] are important commercial products today, as storage media for audio, video, games, and computer software and data applications. A CD disk is molded of polycarbonate (Section 8.2.2), which has ideal optical and mechanical properties for the application. The disk is 120 mm in diameter and 1.2 mm thick. The data consists of small pits (depressions) in a helical track that begins at a diameter of 46 mm and ends at about 117 mm. The tracks in the spiral are separated by about 1.6 μm. Each pit in the track is about 0.5 μm wide and about 0.8 μm to 3.5 μm long. These dimensions certainly qualify CDs as products of microsystem technology. The corresponding dimensions of DVDs are even smaller, permitting much higher data storage capacities.

Although most of the microfabrication processes are discussed in Section 35.2, the production sequence for CDs is briefly described here, because it is rather unique and uses several processes that are quite conventional. As consumer products, music CDs are mass-produced by plastic injection molding (Section 13.6). To make the mold, a master is created from a smooth, thin layer of positive photoresist coated onto a 300-mm diameter glass plate. A modulated laser beam writes the data onto the photoresist by exposing microscopic regions on the surface as the plate is rotated and moved slowly and precisely to create the spiral track. When the photoresist is developed, the exposed regions are removed. These regions in the master will correspond to the pits in the CD. A thin layer of nickel is then deposited onto the surface of the master by sputtering (Section 27.5.1). Electroforming (Section 27.3.2) is then used to build up the thickness of the nickel (to several mm), thus creating a negative impression of the master. This is called the "father." Several impressions are made of the father by the same electroforming process, in effect creating a negative impression

[1]The DVD was originally called a digital video disc because its primary applications were motion picture videos. However, DVDs of various formats are now used for data storage and other computer applications, games, and high-quality audio.

of the father, whose surface geometry is identical to the original glass plate master. These impressions are called "mothers." Finally, the mothers are used to create the actual mold impressions (called "stampers"), again by electroforming, and these are used to mass-produce the CDs.[2] The process sequence is similar for DVDs but more involved because of the smaller scale and different data format requirements.

Once molded, the pitted side of the polycarbonate disk is coated with aluminum by sputtering to create a mirror surface. To protect this layer, a thin polymer coating (e.g., acrylic) is deposited onto the metal. Thus, the final compact disk is a sandwich with a relatively thick polycarbonate substrate on one side, a thin polymer layer on the other side, and in between a very thin layer of aluminum. In subsequent operation, the laser beam of a CD player (or other data reader) is directed through the polycarbonate substrate onto the reflective surface, and the reflected beam is interpreted as a sequence of binary digits.

Automotive Microsensors and other microdevices are widely used in modern automotive products. Use of these microsystems is consistent with the increased application of on-board electronics to accomplish control and safety functions for the vehicle. The functions include electronic engine control, cruise control, anti-lock braking systems, air-bag deployment, automatic transmission control, power steering, all-wheel drive, automatic stability control, on-board navigation systems, and remote locking and unlocking, not to mention air conditioning and radio. These control systems and safety features require sensors and actuators, and a growing number of these are microscopic in size. There are currently 20 to 100 sensors installed in a modern automobile, depending on make and model. In 1970 there were virtually no on-board sensors. Some specific on-board microsensors are listed in Table 35.1.

Medical Opportunities for using microsystems technology in this area are tremendous. Indeed, significant strides have already been made, and many of the traditional medical and surgical methods have already been transformed by MST. One of the driving forces behind the use of microscopic devices is the principle of minimal-invasive therapy, which involves the use of very small incisions or even available body orifices to access the medical problem of concern. Advantages of this approach over the use of relatively large surgical incisions include less patient discomfort, quicker recovery, fewer and smaller scars, shorter hospital stays, and lower health insurance costs.

Among the techniques based on miniaturization of medical instrumentation is the field of endoscopy,[3] now routinely used for diagnostic purposes and with growing applications in surgery. It is standard medical practice today to use endoscopic examination accompanied by laparoscopic surgery for hernia repair and removal of organs such as gall bladder and appendix. Growing use of similar procedures is expected in brain surgery, operating through one or more small holes drilled through the skull.

Other applications of MST in the medical field now include or are expected to include (1) angioplasty, in which damaged blood vessels and arteries are repaired

[2]The reason for the rather involved mold-making sequence is because the pitted surfaces of the impressions degrade after multiple uses. A father can be used to make three to six mothers, and each mother can be used to make three to six stampers, before their respective surfaces become degraded. A stamper (mold) can be used to produce only a few thousand disks, so if the production run is for several hundred thousand CDs, more than one stamper must be used during the run to produce all high-quality CDs.

[3]Endoscopy involves the use of a small instrument (i.e., an endoscope) to visually examine the inside of a hollow body organ such as the rectum or colon.

TABLE • 35.1 Microsensors installed in a modern automobile.

Microdevice	Application(s)
Accelerometer	Air-bag release, antilock brakes, active suspension system
Angular speed sensor	Intelligent navigation systems
Level sensors	Sense oil and gasoline levels
Optical sensor	Automatic headlight control
Position sensor	Transmission, engine timing,
Pressure sensors	Optimize fuel consumption, sense oil pressure, fluid pressures of hydraulic systems (e.g., suspension systems), lumbar seat support pressure, climate control, tire pressure
Proximity and range sensors	Sense distances from front and rear bumpers for parking control and collision prevention
Temperature sensors	Cabin climate control, engine management system
Torque sensor	Drive train

Compiled from [1] and [5].

using surgery, lasers, or miniaturized inflatable balloons at the end of a catheter that is inserted into the vein; (2) telemicrosurgery, in which a surgical operation is performed remotely using a stereo microscope and microscopic surgical tools; (3) artificial prostheses, such as heart pacemakers and hearing aids; (4) implantable sensor systems to monitor physical variables in the human body such as blood pressure and temperature; (5) drug delivery devices that can be swallowed by a patient and then activated by remote control at the exact location intended for treatment, such as the intestine, and (6) artificial eyes.

Chemical and Environmental A principal role of microsystem technology in chemical and environmental applications is the analysis of substances to measure trace amounts of chemicals or detect harmful contaminants. A variety of chemical microsensors have been developed. They are capable of analyzing very small samples of the substance of interest. Micropumps are sometimes integrated into these systems so that the proper amounts of the substance can be delivered to the sensor component.

Other Applications There are many other applications of microsystem technology beyond those described above. Some examples are in the following:

- ***Scanning probe microscope***. This is a technology for measuring microscopic details of surfaces, allowing surface structures to be examined at the nanometer level. To operate in this dimensional range, the instruments require probes that are only a few microns in length and that scan the surface at a distance measured in nanometers. These probes are produced using microfabrication techniques.[4]

[4]Scanning probe microscopes are discussed in Section 36.1.2.

- ➢ ***Biotechnology***. In biotechnology, the specimens of interest are often microscopic in size. To study these specimens, manipulators and other tools are needed that are of the same size scale. Microdevices are being developed for holding, moving, sorting, dissecting, and injecting the small samples of biomaterials under a microscope.
- ➢ ***Electronics***. Printed circuit board (PCB) and connector technologies are discussed in Chapter 34, but they should also be cited here in the context of MST. Miniaturization trends in electronics have forced PCBs, contacts, and connectors to be fabricated with smaller and more complex physical details, and with mechanical structures that are more consistent with the microdevices discussed in this chapter than with the integrated circuits discussed in Chapter 33.

35.2 Microfabrication Processes

Many of the products in microsystem technology are based on silicon, and most of the processing techniques used in the fabrication of microsystems are borrowed from the microelectronics industry. There are several important reasons why silicon is a desirable material in MST: (1) The microdevices in MST often include electronic circuits, so both the circuit and the microdevice can be fabricated in combination on the same substrate. (2) In addition to its desirable electronic properties, silicon also possesses useful mechanical properties, such as high strength and elasticity, good hardness, and relatively low density.[5] (3) The technologies for processing silicon are well- established, owing to their widespread use in microelectronics. (4) Use of single-crystal silicon permits the production of physical features to very close tolerances.

Microsystem technology often requires silicon to be fabricated along with other materials to obtain a particular microdevice. For example, microactuators often consist of several components made of different materials. Accordingly, microfabrication techniques consist of more than just silicon processing. The coverage of the microfabrication processes is organized into three sections: (1) silicon layering processes, (2) the LIGA process, and (3) other processes accomplished on a microscopic scale.

35.2.1 SILICON LAYER PROCESSES

The first application of silicon in microsystems technology was in the fabrication of Si piezoresistive sensors for the measurement of stress, strain, and pressure in the early 1960s [5]. Silicon is now widely used in MST to produce sensors, actuators, and other microdevices. The basic processing technologies are those used to produce integrated circuits (Chapter 33). However, it should be noted that certain differences exist between the processing of ICs and the fabrication of the microdevices covered in this chapter:

1. The aspect ratios in microfabrication are generally much greater than in IC fabrication. ***Aspect ratio*** is defined as the height-to-width ratio of the features produced, as illustrated in Figure 35.6. Typical aspect ratios in semiconductor processing are about 1.0 or less, whereas in microfabrication the corresponding ratio might be as high as 400 [5].

[5]Silicon is discussed in Section 7.5.2.

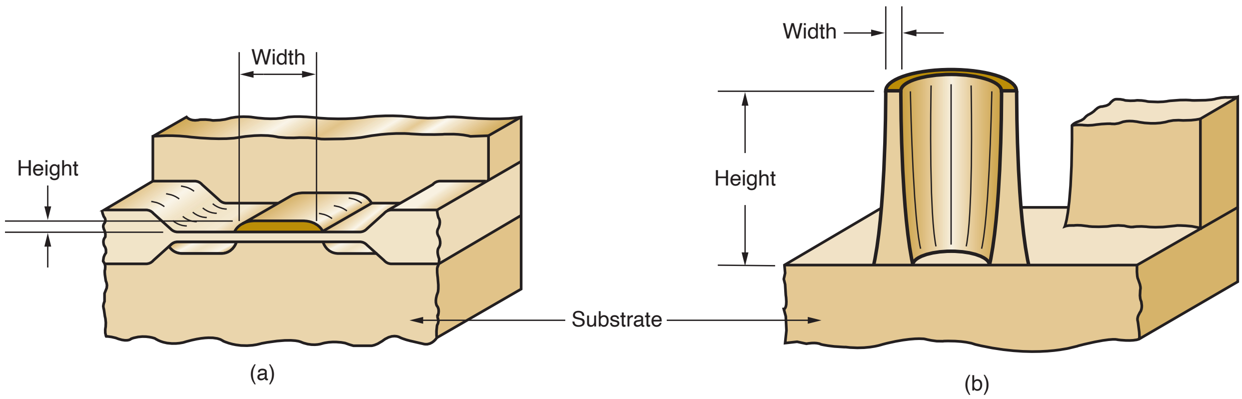

FIGURE 35.6 Aspect ratio (height-to-width ratio) typical in (a) fabrication of integrated circuits and (b) microfabricated components.

2. The sizes of the devices made in microfabrication are often much larger than in IC processing, in which the prevailing trend in microelectronics is inexorably toward greater circuit densities and miniaturization.
3. The structures produced in microfabrication often include cantilevers and bridges and other shapes requiring gaps between layers. These kinds of structures are uncommon in IC fabrication.
4. The usual silicon processing techniques are sometimes supplemented to obtain a three-dimensional structure or other physical feature in the microsystem.

Notwithstanding these differences, it must nevertheless be recognized that most of the silicon-processing steps used in microfabrication are the same or very similar to those used to produce ICs. After all, silicon is the same material whether it is used for integrated circuits or microdevices. The processing steps are listed in Table 35.2, together with brief descriptions and text references where the reader can obtain more detailed descriptions. All of these process steps are discussed in previous chapters. As in IC fabrication, the various processes in Table 35.2 add, alter, or remove layers of material from a substrate according to geometric data contained in lithographic masks. Lithography is the fundamental technology that determines the shape of the microdevice being fabricated.

Regarding the preceding list of differences between IC fabrication and microdevice fabrication, the issue of aspect ratio should be addressed in more detail. The structures in IC processing are basically planar, whereas three-dimensional structures are more likely to be required in microsystems. The features of microdevices are likely to possess large height-to-width ratios. These 3-D features can be produced in single-crystal silicon by wet etching, provided the crystal structure is oriented to allow the etching process to proceed anisotropically. Chemical wet etching of polycrystalline silicon is isotropic, with the formation of cavities under the edges of the resist, as illustrated in Figure 33.16. However, in single-crystal Si, the etching rate depends on the orientation of the lattice structure. In Figure 35.7, the three crystal faces of silicon's cubic lattice structure are illustrated. Certain etching solutions, such as potassium hydroxide (KOH) and sodium hydroxide (NaOH), have a very low etching rate in the direction of the (111) crystal face. This permits the formation of

TABLE • 35.2 Silicon layering processes used in microfabrication.

Process	Brief Description	Text Reference
Lithography	Printing process used to transfer copies of a mask pattern onto the surface of silicon or other solid material (e.g., silicon dioxide). The usual technique in microfabrication is photolithography.	Section 33.3
Thermal oxidation	(Layer addition) Oxidation of silicon surface to form silicon dioxide layer.	Section 33.4.1
Chemical vapor deposition	(Layer addition) Formation of a thin film on the surface of a substrate by chemical reactions or decomposition of gases.	Sections 27.5.2 and 33.4.2
Physical vapor deposition	(Layer addition) Family of deposition processes in which a material is converted to vapor phase and condensed onto a substrate surface as a thin film. PVD processes include vacuum evaporation and sputtering.	Section 27.5.1
Electroplating and electroforming	(Layer addition) Electrolytic process in which metal ions in solution are deposited onto a cathode work material.	Sections 27.3.1 and 27.3.2
Electroless plating	(Layer addition) Deposition in an aqueous solution containing ions of the plating metal with no external electric current. Work surface acts as catalyst for the reaction.	Section 27.3.3
Thermal diffusion (doping)	(Layer alteration) Physical process in which atoms migrate from regions of high concentration into regions of low concentration.	Sections 27.2.1 and 33.4.3
Ion implantation (doping)	(Layer alteration) Embedding atoms of one or more elements in a substrate using a high-energy beam of ionized particles.	Sections 27.2.2 and 33.4.3
Wet etching	(Layer removal) Application of a chemical etchant in aqueous solution to etch away a target material, usually in conjunction with a mask pattern.	Section 33.4.5
Dry etching	(Layer removal) Dry plasma etching using an ionized gas to etch a target material.	Section 33.4.5

distinct geometric structures with sharp edges in a single-crystal Si substrate whose lattice is oriented to favor etch penetration vertically or at sharp angles into the substrate. Structures such as those in Figure 35.8 can be created using this procedure. It should be noted that anisotropic wet etching is also desirable in IC fabrication

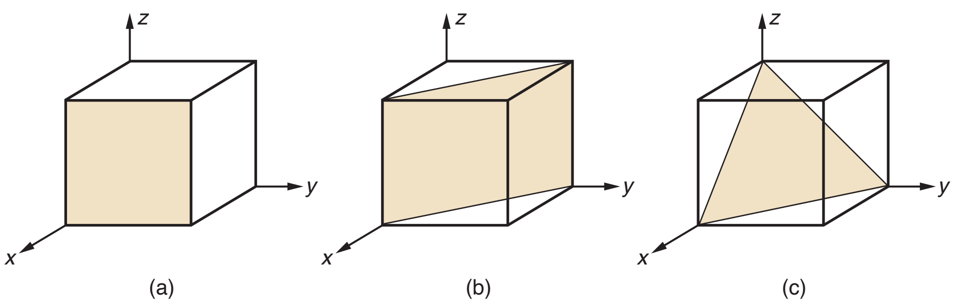

FIGURE 35.7 Three crystal faces in the silicon cubic lattice structure: (a) (100) crystal face, (b) (110) crystal face, and (c) (111) crystal face.

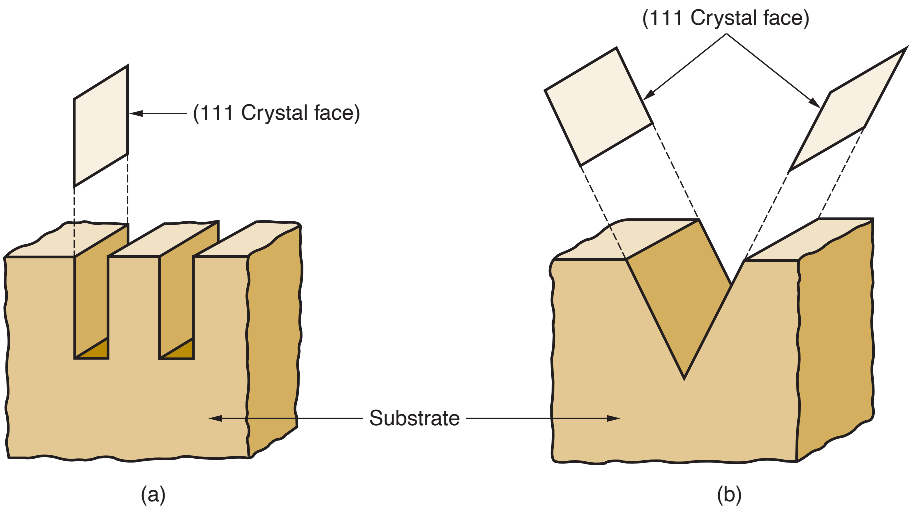

FIGURE 35.8 Several structures that can be formed in single-crystal silicon substrate by bulk micromachining: (a) (110) silicon and (b) (100) silicon.

(Section 33.4.5), but its consequence is greater in microfabrication because of the larger aspect ratios. The term ***bulk micromachining*** is used for the relatively deep wet etching process into single-crystal silicon substrate (Si wafer); whereas the term ***surface micromachining*** refers to the planar structuring of the substrate surface, using much more shallow layering processes.

Bulk micromachining can be used to create thin membranes in a microstructure. However, a method is needed to control the etching penetration into the silicon, so as to leave the membrane layer. A common method used for this purpose is to dope the silicon substrate with boron atoms, which significantly reduce the etching rate of the silicon. The processing sequence is shown in Figure 35.9. In step (2), epitaxial deposition is used to apply the upper layer of silicon so that it will possess the same single-crystal structure and lattice orientation as the substrate (Section 33.4.2). This is a requirement of bulk micromachining that will be used to provide the deeply etched region in subsequent processing. The use of boron doping to establish the etch resistant layer of silicon is called the ***p^+ etch-stop technique***.

Surface micromachining can be used to construct cantilevers, overhangs, and similar structures on a silicon substrate, as shown in part (5) of Figure 35.10. The cantilevered

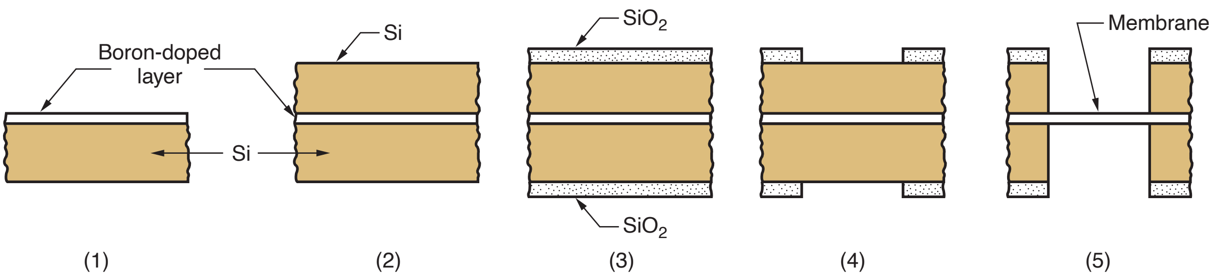

FIGURE 35.9 Formation of a thin membrane in a silicon substrate: (1) silicon substrate is doped with boron; (2) a thick layer of silicon is applied on top of the doped layer by epitaxial deposition; (3) both sides are thermally oxidized to form a SiO_2 resist on the surfaces; (4) the resist is patterned by lithography; and (5) anisotropic etching is used to remove the silicon except in the boron-doped layer.

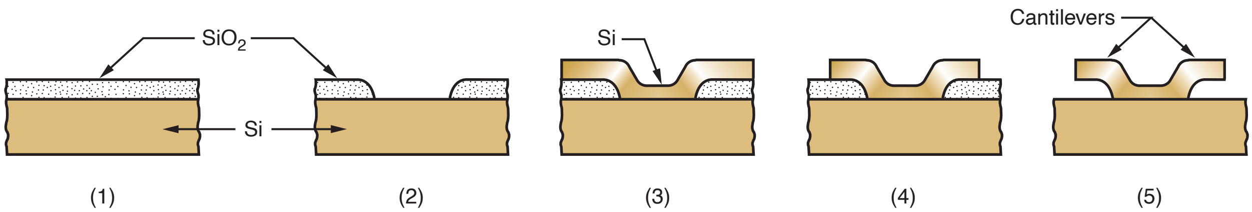

FIGURE 35.10 Surface micromachining to form cantilevers: (1) on the silicon substrate is formed a silicon dioxide layer, whose thickness will determine the gap size for the cantilevered member; (2) portions of the SiO_2 layer are etched using lithography; (3) a polysilicon layer is applied; (4) portions of the polysilicon layer are etched using lithography; and (5) the SiO_2 layer beneath the cantilevers is selectively etched.

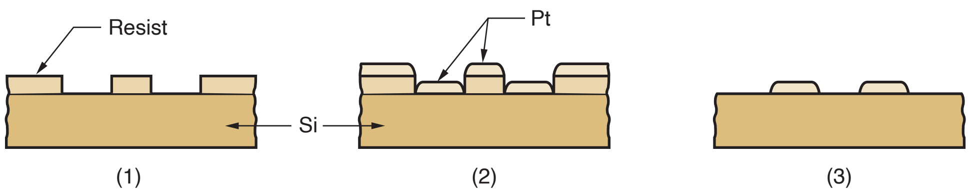

FIGURE 35.11 The lift-off technique: (1) resist is applied to substrate and structured by lithography; (2) platinum is deposited onto surfaces; and (3) resist is removed, taking with it the platinum on its surface but leaving the desired platinum microstructure.

beams in the figure are parallel to but separated by a gap from the silicon surface. Gap size and beam thickness are in the micron range. The process sequence to fabricate this type of structure is depicted in the earlier parts of Figure 35.10.

Dry etching, which involves material removal through the physical and/or chemical interaction between the ions in an ionized gas (a plasma) and the atoms of a surface that has been exposed to the ionized gas (Section 33.4.5), provides anisotropic etching in almost any material. Its anisotropic penetration characteristic is not limited to a single-crystal silicon substrate. On the other hand, etch selectivity is more of a problem in dry etching; that is, any surfaces exposed to the plasma are attacked.

A procedure called the ***lift-off technique*** is used in microfabrication to pattern metals such as platinum on a substrate. These structures are used in certain chemical sensors, but are difficult to produce by wet etching. The processing sequence in the lift-off technique is illustrated in Figure 35.11.

35.2.2 LIGA PROCESS

LIGA is an important process in MST. It was developed in Germany in the early 1980s, and the letters ***LIGA*** stand for the German words ***LI***thographie (in particular, X-ray lithography, although other lithographic exposure methods are also used, such as ion beams in Figure 35.3), ***G***alvanoformung (translated electrodeposition or electroforming), and ***A***bformtechnik (plastic molding). The letters also indicate the LIGA processing sequence. These processing steps have each been described in previous sections of this book: X-ray lithography in Section 33.3.2; electrodeposition and electroforming in Sections 27.3.1 and 27.3.2, respectively; and plastic molding processes in Sections 13.6 and 13.7. The integration of these steps in LIGA technology is examined in this section.

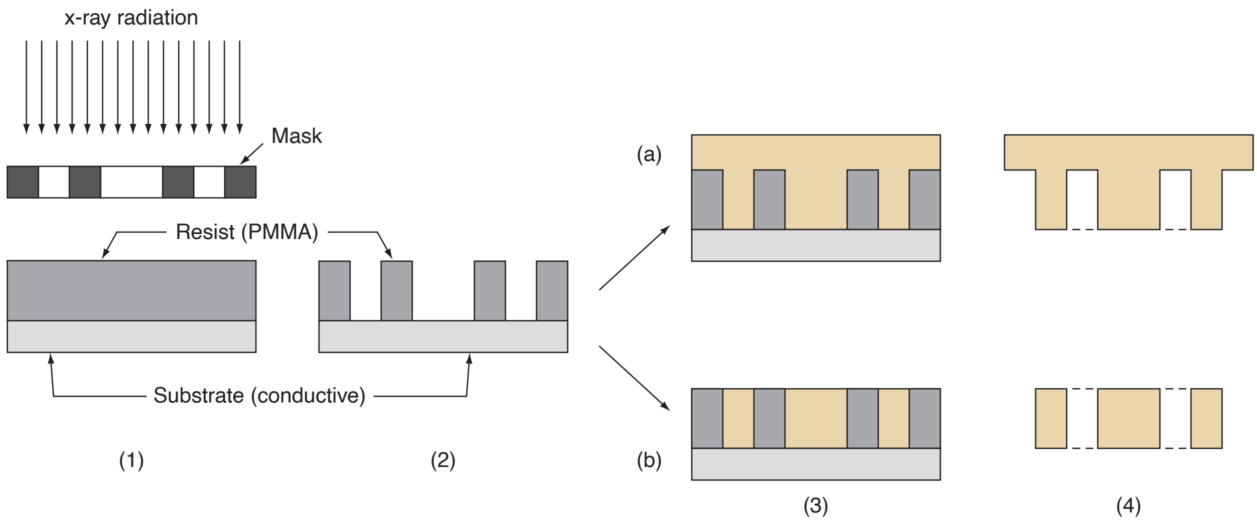

FIGURE 35.12 LIGA processing steps: (1) thick layer of resist applied and X-ray exposure through mask, (2) exposed portions of resist removed, (3) electrodeposition to fill openings in resist, (4) resist stripped to provide (a) a mold or (b) a metal part.

The LIGA process is illustrated in Figure 35.12. The brief description provided in the figure's caption needs to be expanded: (1) A thick layer of (X-ray) radiation-sensitive resist is applied to a substrate. Layer thickness can range between several microns to centimeters, depending on the size of the part(s) to be produced. The common resist material used in LIGA is polymethylmethacrylate (PMMA, Section 8.2.2 under "Acrylics"). The substrate must be a conductive material for the subsequent electrodeposition processes performed. The resist is exposed through a mask to high-energy X-ray radiation. (2) The irradiated areas of the positive resist are chemically removed from the substrate surface, leaving the unexposed portions standing as a three-dimensional plastic structure. (3) The regions where the resist has been removed are filled with metal using electrodeposition. Nickel is the common plating metal used in LIGA. (4) The remaining resist structure is stripped (removed), yielding a three-dimensional metal structure. Depending on the geometry created, this metallic structure may be (a) the mold used for producing plastic parts by injection molding, reaction injection molding, or compression molding. In the case of injection molding, in which thermoplastic parts are produced, these parts may be used as "lost molds" in investment casting (Section 11.2.4). Alternatively, (b) the metal part may be a pattern for fabricating plastic molds that will be used to produce more metallic parts by electrodeposition.

As the description indicates, LIGA can produce parts by several different methods. This is one of the greatest advantages of this microfabrication process: (1) LIGA is a versatile process. Other advantages include (2) high aspect ratios are possible in the fabricated part; (3) a wide range of part sizes is feasible, with heights ranging from micrometers to centimeters; and (4) close tolerances can be achieved. A significant disadvantage of LIGA is that it is a very expensive process, so large quantities of parts are usually required to justify its application. Also, the required use of x-ray radiation is a disadvantage.

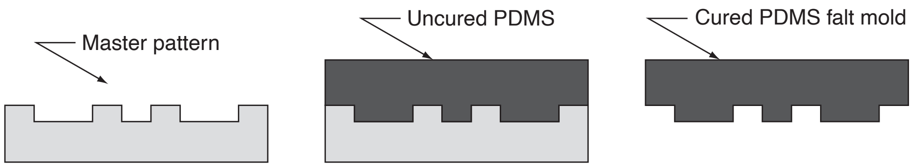

FIGURE 35.13 Steps in mold-making for soft lithography: (1) master pattern fabricated by traditional lithography, (2) polydimethylsiloxane flat mold is cast from the master pattern, and (3) cured flat mold is peeled off pattern for use.

35.2.3 OTHER MICROFABRICATION PROCESSES

MST research is providing several additional fabrication techniques, most of which are variations of lithography or adaptations of macro-scale processes. This section discusses several of these additional techniques.

Soft Lithography This term refers to processes that use an elastomeric flat mold (similar to a rubber ink stamp) to create a pattern on a substrate surface. The sequence for creating the mold is illustrated in Figure 35.13. A master pattern is fabricated on a silicon surface using one of the lithography processes such as UV photolithography or electron beam lithography. This master pattern is then used to produce the flat mold for the soft lithography process. The common mold material is polydimethylsiloxane (PDMS, a silicon rubber, Section 8.4.3). After the PDMS has cured, it is peeled away from the pattern and attached to a substrate for support and handling.

Two of the soft lithography processes are micro-imprint lithography and microcontact printing. In ***micro-imprint lithography***, the mold is pressed into the surface of a soft resist to displace the resist away from certain regions of the substrate for subsequent etching. The process sequence is illustrated in Figure 35.14. The flat mold consists of raised and depressed regions, and the raised regions correspond to areas on the resist surface that will be displaced to expose the substrate. The resist material is a thermoplastic polymer that has been softened by heating before pressing. The alteration of the resist layer is by mechanical deformation rather than electromagnetic radiation, as in the more traditional lithography methods. The compressed regions of the resist layer are subsequently removed by anisotropic etching (Section 34.4.5). The etching process also reduces the thickness of

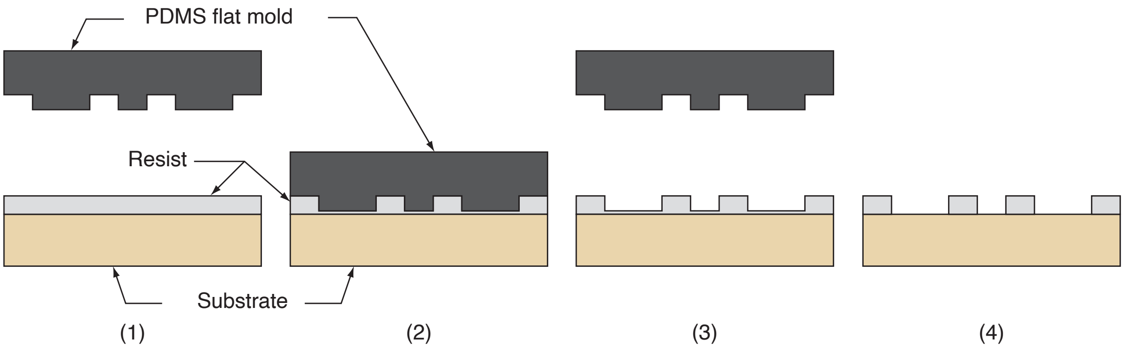

FIGURE 35.14 Steps in micro-imprint lithography:(1) mold positioned above and (2) pressed into resist, (3) mold is lifted, and (4) remaining resist is removed from substrate surface in defined regions.

the remaining resist layer, but enough remains to protect the substrate for subsequent processing. Micro-imprint lithography can be set up for high production rates at modest cost. A mask is not required in the imprint procedure, although the mold requires an analogous preparation.

The same type of flat stamp can be used in a printing mode, in which case the process is called ***micro-contact printing***. In this form of soft lithography, the mold is used to transfer a pattern of a substance to a substrate surface, much like ink can be transferred to a paper surface. This process allows very thin layers to be fabricated onto the substrate.

Nontraditional and Traditional Processes in Microfabrication A number of nontraditional machining processes (Chapter 25), as well as conventional manufacturing processes, are important in microfabrication. ***Photochemical machining*** (PCM, Section 25.4.2) is an essential process in IC processing and microfabrication, but it has been referred to in previous descriptions here and in Chapter 33 as wet chemical etching (combined with photolithography). PCM is often used with conventional processes of ***electroplating, electroforming***, and/or ***electroless plating*** (Section 27.3) to add layers of metallic materials according to microscopic pattern masks.

Other nontraditional processes capable of micro-level processing include [5]: (1) ***electric discharge machining***, used to cut holes as small as 0.3 mm in diameter with aspect ratios (depth-to-diameter) as high as 100; (2) ***electron-beam machining***, for cutting holes of diameter smaller than 100 μm in hard-to-machine materials; (3) ***laser-beam machining***, which can produce complex profiles and holes as small as 10 μm in diameter with aspect ratios (depth-to-width or depth-to-diameter) approaching 50; (4) ***ultrasonic machining***, capable of drilling holes in hard and brittle materials as small as 50 μm in diameter; and (5) ***wire electric discharge cutting***, or ***wire-EDM***, which can cut very narrow swaths with aspect ratios (depth-to-width) greater than 100.

Trends in conventional machining have included its capabilities for taking smaller and smaller cut sizes and associated tolerances. Referred to as ***ultra-high-precision machining***, the enabling technologies have included single-crystal diamond cutting tools and position control systems with resolutions as fine as 0.01 μm [5]. Figure 35.15 depicts one reported application, the milling of grooves in

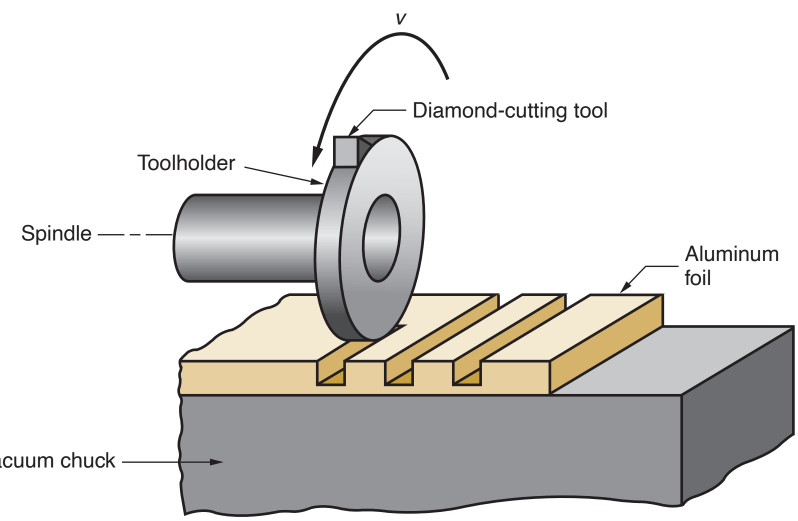

FIGURE 35.15 Ultra-high-precision milling of grooves in aluminum foil.

aluminum foil using a single-point diamond fly-cutter. The aluminum foil is 100 μm thick, and the grooves are 85 μm wide and 70 μm deep. Similar ultra-high-precision machining is being applied today to produce products such as computer hard discs, photocopier drums, mold inserts for compact disk reader heads, and high-definition TV projection lenses.

Rapid Prototyping Technologies Several rapid prototyping (RP) methods (Chapter 32) have been adapted to produce micro-sized parts [7]. RP methods use a layer additive approach to build three-dimensional components, based on a CAD (computer-aided design) geometric model of the component. Each layer is very thin, typically as low as 0.05 mm thick, which approaches the scale of microfabrication technologies. By making the layers even thinner, microcomponents can be fabricated.

One approach is called ***electrochemical fabrication*** (EFAB), which involves the electrochemical deposition of metallic layers in specific areas that are determined by pattern masks created by "slicing" a CAD model of the object to be made (Section 33.1). The deposited layers are generally 5 to 10 μm thick, with feature sizes as small as 20 μm in width. EFAB is carried out at temperatures below 60°C (140°F) and does not require a clean room environment. However, the process is slow, requiring about 40 minutes to apply each layer, or about 35 layers (a height between 180 and 360 μm) per 24-hour period. To overcome this disadvantage, the mask for each layer can contain multiple copies of the part slice pattern, permitting many parts to be produced simultaneously in a batch process.

Another RP approach, called ***microstereolithography***, is based on stereolithography (STL, Section 32.2.1), but the scale of the processing steps is reduced in size. Whereas the layer thickness in conventional stereolithography ranges between 75 μm and 500 μm, microstereolithography (MSTL) uses layer thicknesses between 10 and 20 μm typically, with even thinner layers possible. The laser spot size in STL is typically around 250 μm in diameter, whereas MSTL uses a spot size as small as 1 or 2 μm. Another difference in MSTL is that the work material is not limited to a photosensitive polymer. Researchers report success in fabricating 3-D microstructures from ceramic and metallic materials. The difference is that the starting material is a powder rather than a liquid.

Photofabrication This term applies to an industrial process in which ultraviolet exposure through a pattern mask causes a significant modification in the chemical solubility of an optically clear material. The change is manifested in the form of an increase in solubility to certain etchants. For example, hydrofluoric acid etches the UV-exposed photosensitive glass between 15 and 30 times faster than the same glass that has not been exposed. Masking is not required during etching, the difference in solubility being the determining factor in which portions of the glass are removed.

Origination of photofabrication actually preceded the microprocessing of silicon. Now, with the growing interest in microfabrication technologies, there is a renewed interest in the older technology. Examples of modern materials used in photofabrication include Corning Glass Works' Fotoform(tm) glasses and Fotoceram(tm) ceramics, and DuPont's Dycril and Templex photosensitive solid polymers. When processing these materials, aspect ratios of around 3:1 can be obtained with the polymers and 20:1 with the glasses and ceramics.