CHAPTER 1

OVERVIEW OF MEMS AND MICROSYSTEMS

1.1 MEMS AND MICROSYSTEMS

The term MEMS is an abbreviation of microelectromechanical system. A MEMS contains components of sizes ranging from one micrometer (μm) to one millimeter (mm) (1 mm = 1000 μm). A MEMS is constructed to achieve a certain engineering function or functions by electromechanical or electrochemical means.

The core element in MEMSs generally consists of two principal components: a sensing and/or an actuating element and a signal transduction unit. Figure 1.1 illustrates the functional relationship between these components in a microsensor.

Microsensors are built to sense the existence and the intensity of certain physical, chemical, or biological quantities such as temperature, pressure, force, sound, light, nuclear radiation, magnetic flux, and chemical and biological compositions. Microsensors have the advantages of being sensitive and accurate with minimal amount of required sample substance. They can also be mass produced in batches with large volumes.

There are many different types of microsensors developed for a variety of applications, and they are widely used in industry. Common sensors include biosensors, chemical sensors, optical sensors, and thermal and pressure sensors. Working principles of these sensors will be presented in Chapter 2. In a pressure sensor, an input signal such as pressure from a source is sensed by a microsensing element, which may include simply a thin silicon diaphragm only a few micrometers as illustrated in Figures 1.22*c* and 2.8. The deflection of the diaphragm induced by the applied pressure is converted into a change of electrical resistance by micropiezoresistors that are implanted in the diaphragm. These piezoresistors constitute a part of the transduction unit. The change of electrical resistance in the piezoresistors induced by the change of the induced maximum stresses can be further converted into corresponding voltage changes using a micro–Wheatstone

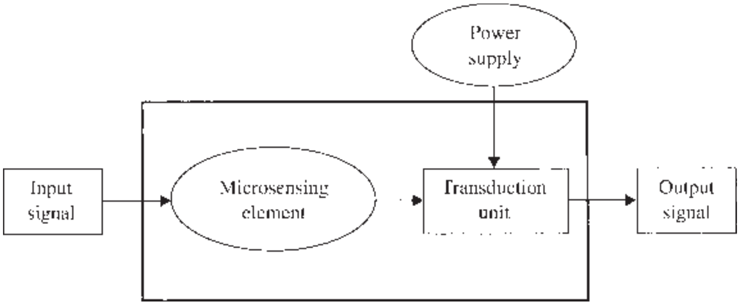


Figure 1.1. MEMS as a microsensor.

bridge circuit also attached to the sensing element as another part of the transduction unit (see Figure 2.9). The output signal of this type of microsensor is thus in the voltage change corresponding to the input pressure. Typical micro–pressure sensors are shown as packaged products in Figure 1.2.

There are many other types of microsensors that are either available in the marketplace or are being developed. They include chemical sensors for detecting chemicals or toxic gases such as CO, CO_2, NO, O_3, and NH_3, either from exhaust from a combustion or a fabrication process or from the environment for air quality control.

Biomedical sensors and biosensors have enjoyed significant share in the microsensor market in recent years. Micro–biomedical sensors are mainly used for diagnosis analyses. Because of their miniature size, these sensors typically require minute amount of sample and can produce results significantly faster than the traditional biomedical instruments. Moreover, these sensors can be produced in batches, resulting in low unit cost. Another cost saving is that most of these sensors are disposable; manual labor involving cleaning and proper treatments for reuse can be avoided. Biosensors are extensively used in analytical chemistry and biomedicine as well as genetic engineering.

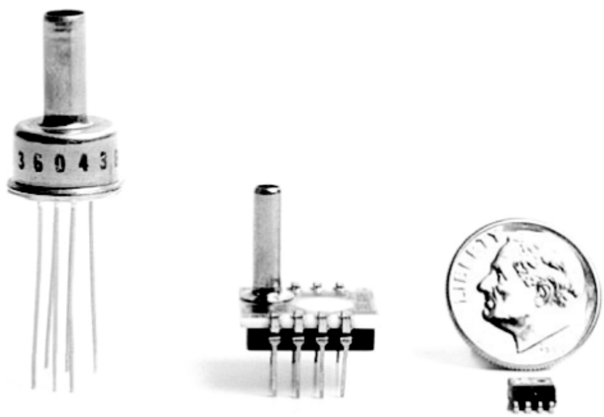


Figure 1.2. Micro–pressure sensor packages.

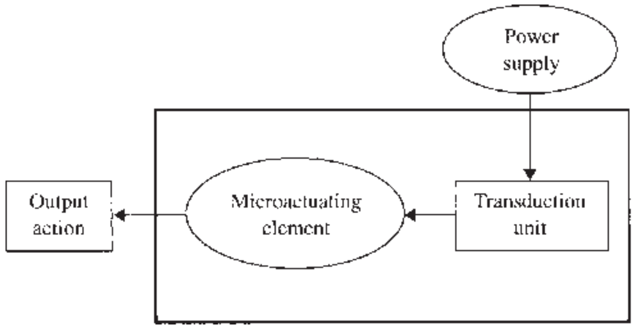


Figure 1.3. MEMS as a microactuator.

Working principles for many of these microsensors will be presented in Section 2.2. Chapters 4 and 5 will present the design methodologies for these sensors.

Figure 1.3 illustrates the functional relationship between the sensing element and the transduction unit in a microactuator. The transduction unit converts the input power supply into the form such as voltage for a transducer, which functions as the actuating element.

There are several ways by which microdevice components can be actuated, as will be described in Section 2.3. One popular actuation method involves using electrostatic forces generated by charged parallel conducting plates or electrodes separated by dielectric material such as air. The arrangement is similar to that of capacitors. The application of input voltage to the plates (i.e., the electrodes in a capacitor) from a direct-current (DC) power source can result in electrostatic forces that prompt relative motion of these plates in the normal direction of aligned plates or parallel movement for misaligned plates. These motions are set to accomplish the required actions. Electrostatic actuation is used in many microactuators. One such application is in a microgripper as illustrated in Figure 1.4. Chapter 2 will include several other actuation methods and for other types of devices.

A *microsystem* is a miniature engineering system that usually contains MEMS components designed to perform specific engineering functions. Despite the fact that many MEMS components can be produced in the size of micrometers, microsystems are typically in “mesoscales.” (There is no clear definition of what constitutes the mesoscale. It implies a scale that is between micro- and macroscales. Conventional wisdom, however, suggests that a mesoscale is in the size range of millimeters to a centimeter.) In a somewhat restricted view, Madou (1997) defines a microsystem to include three major components: microsensors, actuators, and a processing unit. The functional relationship of these three components is illustrated in Figure 1.5.

Figure 1.5 shows that signals received by a sensor or sensors in a microsystem are converted into forms compatible with the actuator through the signal transduction and processing unit. One example of this operation is the airbag deployment system in an automobile, in which the impact of the car in a serious collision is “felt” by a micro–inertia sensor built on the principle of a microaccelerometer, as described in Chapter 2. The sensor generates an appropriate signal to an actuator that deploys the airbag to protect the driver and the passengers from serious injuries.

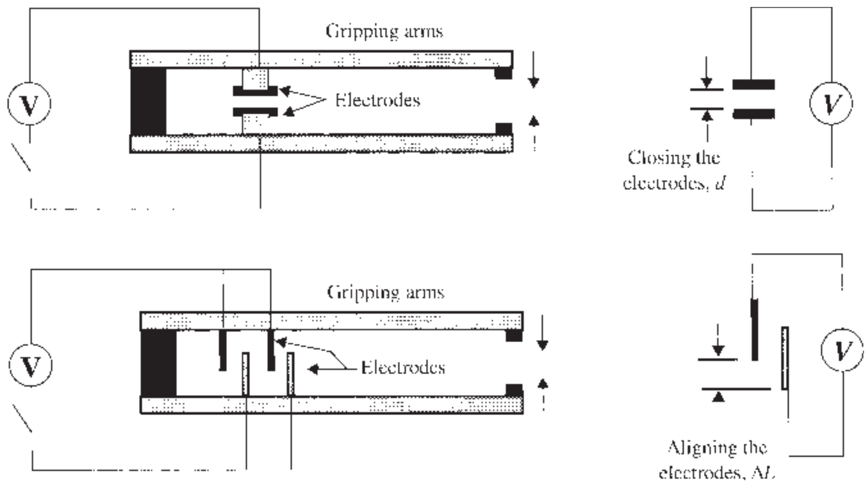


Figure 1.4. MEMS using electrostatic actuation.

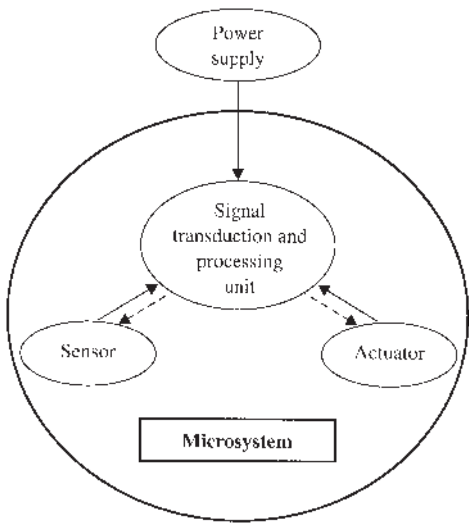


Figure 1.5. Essential components of a microsystem.

Figure 1.6 shows a micro–inertia sensor produced for this purpose. The sensor, which contains two microaccelerometers, is mounted to the chassis of the car. The accelerometer on the left measures the deceleration in the horizontal (x) direction, whereas the unit on the right measures the deceleration in the y direction. Both these accelerometers were mounted on the same integrated circuit (IC) chip with signal transduction and processing units. The entire chip has an approximate size of 3×2 mm, with the microaccelerometers taking about 10% of the overall chip area. The working principle of this type of microaccelerometer will be explained in Section 2.5.

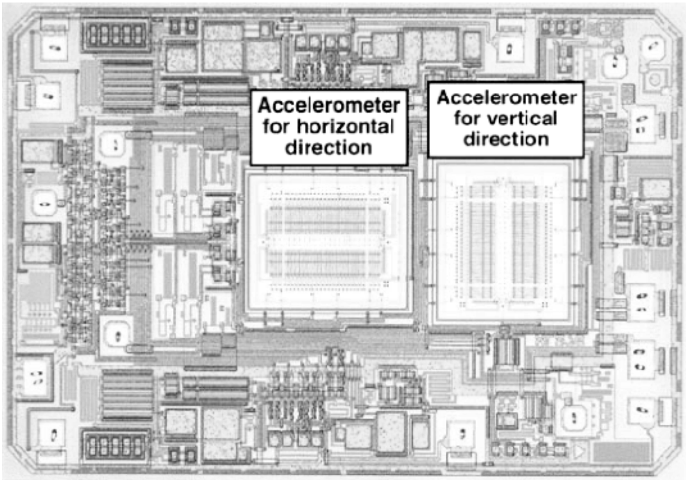


Figure 1.6. Analog Devices ADXL276/ADXL 250 microaccelerometer. (Courtesy of Analog Devices, Norwood, MA.)

Most microsystems are designed and constructed to perform single functions such as presented in this section. There is a clear trend in the industry to incorporate signal processing and close-loop feedback control systems in a microsystem to make the integrated system "intelligent." The arrangement in Figure 1.7 illustrates such a possibility.

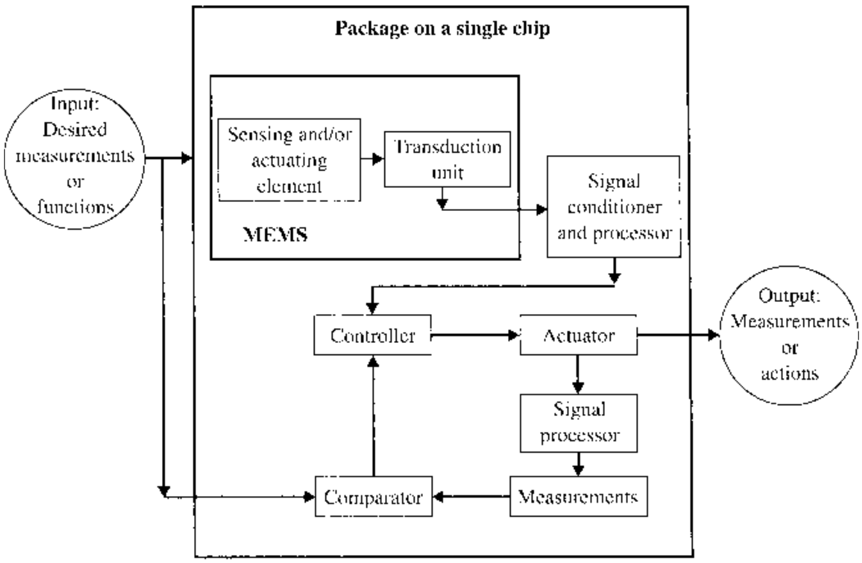
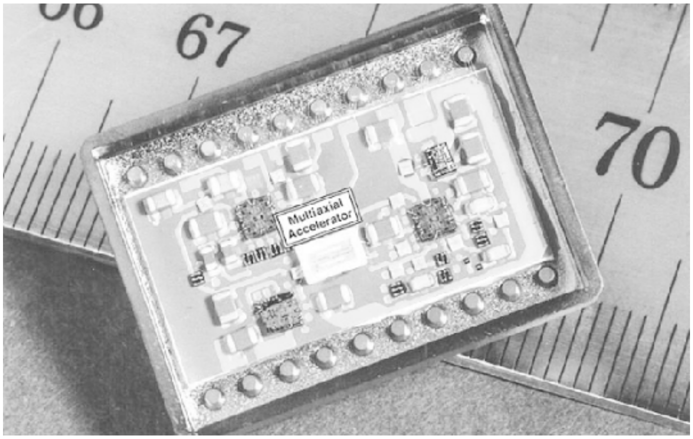


Figure 1.7. Intelligent microsystems.



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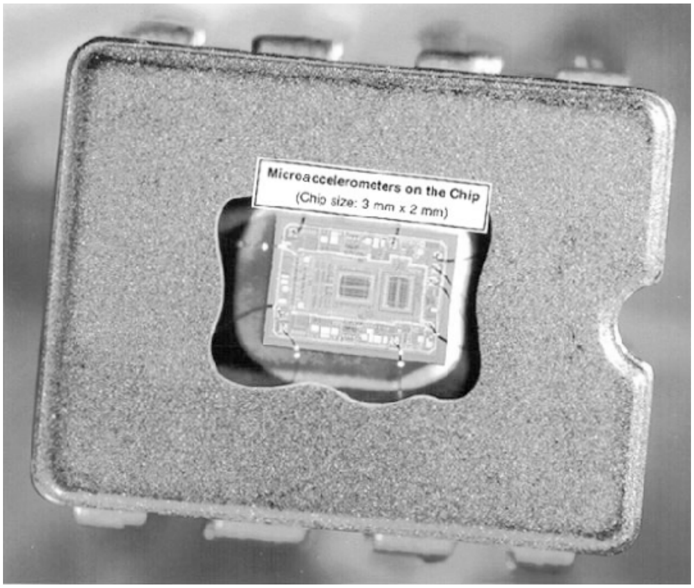

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Figure 1.8. Intelligent inertia sensors used in automobile airbag deployment systems. (*a*) Inertia sensor on chip. (Courtesy of Karlsruhe Nuclear Research Center, Karlsruhe Germany.) (*b*) Packaged sensor on chip. (Courtesy of Analog Devices, Norwwod, MA.)

Many microsystems have been built on the “lab-on-the-chip” concept. The entire unit can be contained in a silicon chip of size less than 0.5×0.5 mm. Figure 1.8 shows such an example for two different designs of microaccelerometers, or inertia sensors used in airbag deployment systems of automobiles.

1.2 TYPICAL MEMS AND MICROSYSTEMS PRODUCTS

Research institutions and industry have made relentless effort in the past two decades in developing and producing smaller and better MEMS devices and components. Many of these miniaturized devices such as silicon gear trains and tongs were reported by Mehregany et al. (1988). Following is a list, with brief descriptions, of the MEMS devices and components that were produced in recent years. The list, of course, is constanlty becoming longer as the micromanufacturing technology advances.

1.2.1 Microgears

Figure 1.9*a* shows a gear made to a size that is significantly smaller than an ant's head, whereas Figure 1.9*b* shows a two-level gear made from ceramics. The pitch of the gears is on the order of 100 μm. Both these gears were produced using the LIGA (a German acronym of Lithographie Galvanoformung Abformung), process as will be described in detail in Chapter 9.

1.2.2 Micromotors

Figure 1.10 shows an electrostatic-driven micromotor produced by the LIGA process (Bley, 1993). All three components—the rotor (the center gear), the stator, and the torque transmission gear—are made of nickel. The toothed rotor, which has a pitch diameter of 700 μm, is engaged to a gear wheel with 250 μm diameter. The latter wheel transmits the torque produced by the motor. The gap between the rotor and the axle and between the rotor and the stator is 4 μm. The height of the unit is 120 μm.

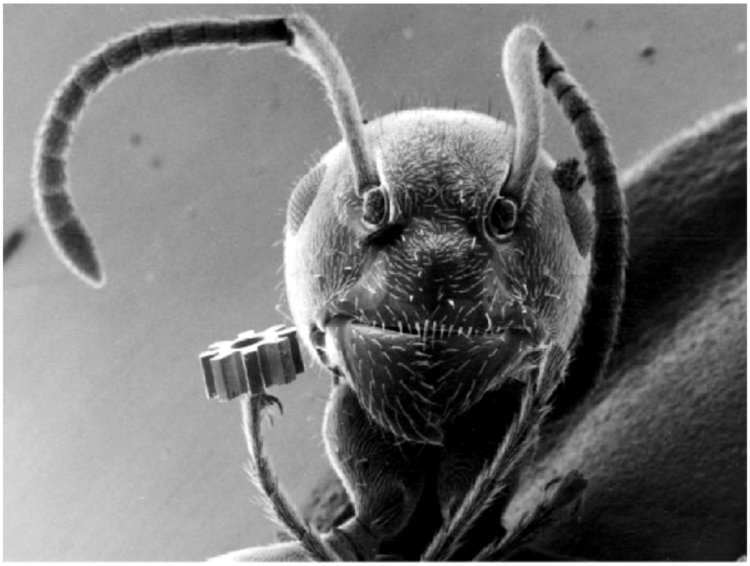
1.2.3 Microturbines

A microturbine was produced to generate power (Bley, 1993). As shown in Figure 1.11, the turbine is made of nickel. The rotor has a diameter of 130 μm. A 5-μm gap is provided between the axle and the rotor. The turbine has a height of 150 μm. The entire unit was made of nickel. The maximum rotational speed reached 150,000 revolutions per minute (rpm) with a lifetime up to 100 million rotations.

1.2.4 Micro-Optical Components

These components are extensively used in high-speed signal transmissions in the telecommunication industry. Here, we will show two such micro-optical components in Figures 1.12 and 1.13. In Figure 1.12 is a micro-optical switch using a silicon-based manufacturing process. These switches are used to regulate incident light from optical fibers (shown as cylinders in the figure) to appropriate receiving optical fibers.

Figure 1.13 shows microlenses made of transparent polymer, poly (methyl methacrylate) (PMMA). Each lens shown on the left has a diameter of 150 μm. These arrays of lenses are combined into micro-objectives for endoscopy with an optical resolution down to 3 μm. These lenses can also be used for copiers, laser scanners, and printers. At the right is a combination of one such lens with a micro-objective for neurosurgery (Bley, 1999).



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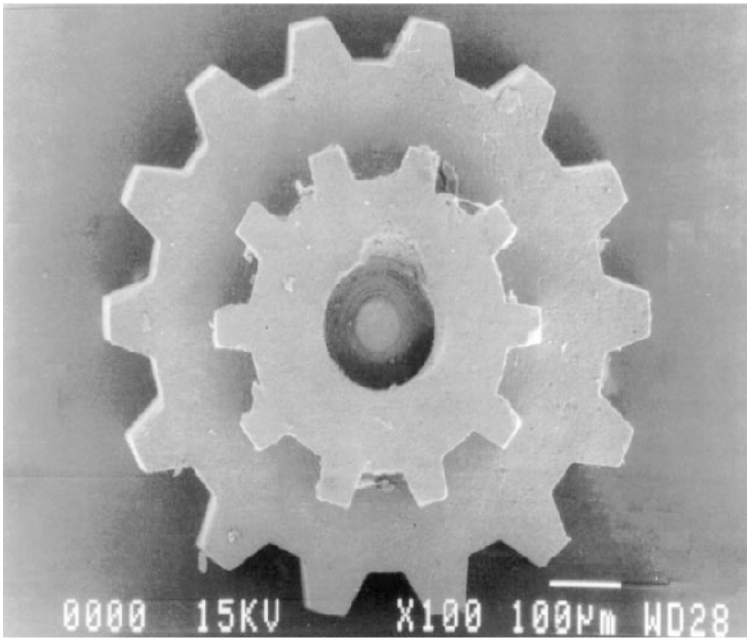

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Figure 1.9. Microgears produced by the LIGA process: (*a*) microgear at tip of ant's leg; (*b*) two-level ceramic gear. (Courtesy of Karlsruhe Nuclear Research Center, Karlsruhe, Germany.)

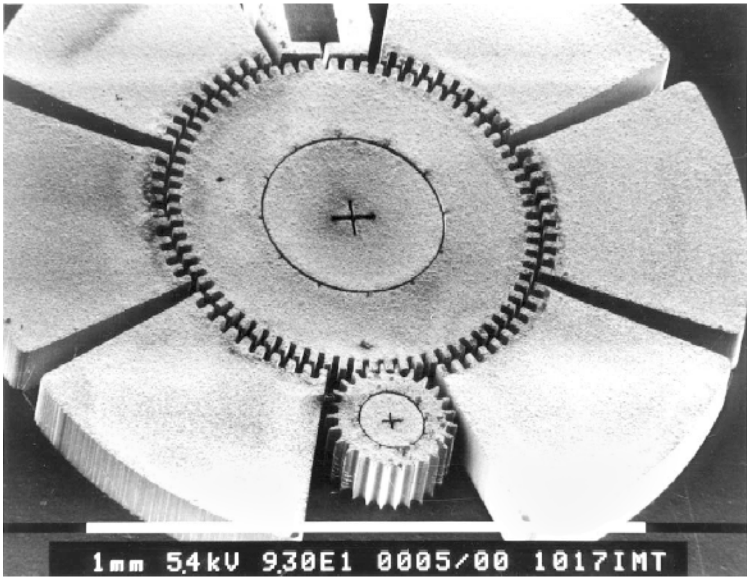

Figure 1.10. Micromotor produced by LIGA process. [Reproduced with permission from Bley (1993).]

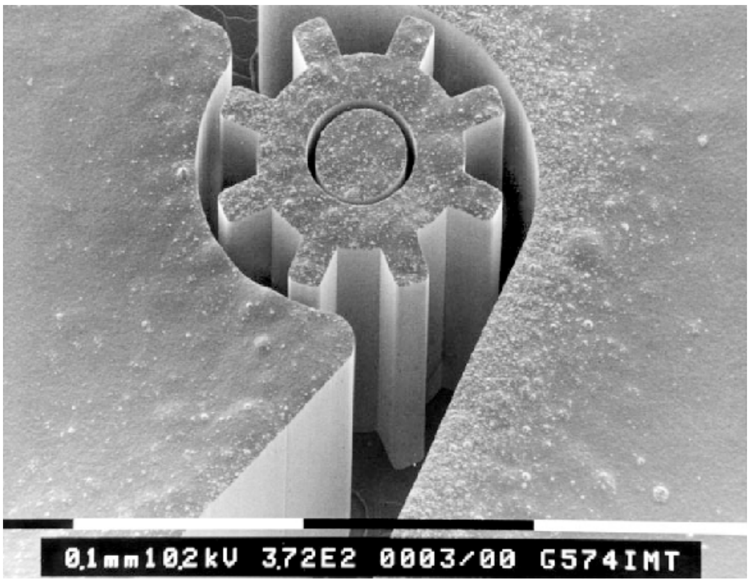

Figure 1.11. Microturbine. [Reproduced with permission from Bley (1993).]

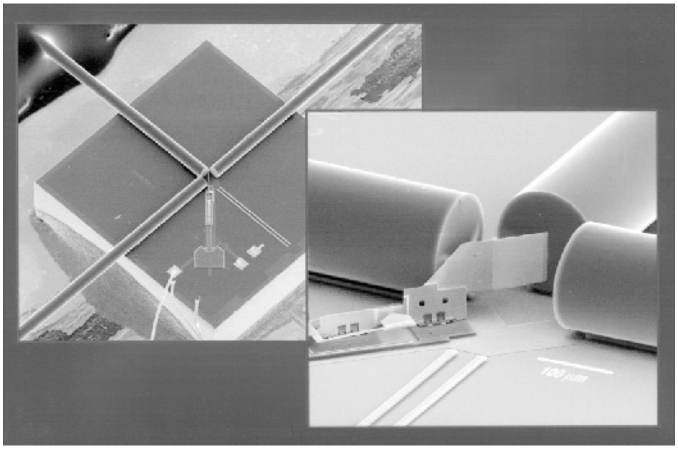

Figure 1.12. Lucent MEMS 1×2 optical switch. (Courtesy of Bell Laboratories of Lucent Technologies.)

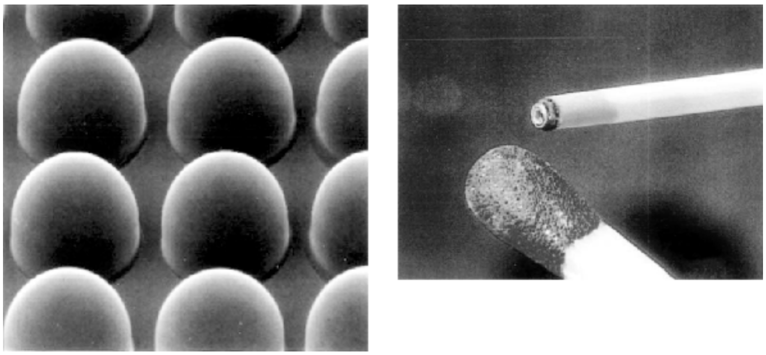

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Figure 1.13. Arrays of high-aperture microlenses. [Reproduced with permission from Bley (1999).]

1.3 EVOLUTION OF MICROFABRICATION

The size of components of microsystems has been decreasing continuously, with some of the MEMS components made in submicrometer sizes. Fabrication of device components of these minute sizes is clearly beyond traditional mechanical means such as machining, drilling, milling, forging, casting, and welding. The technologies used to produce these minute components are called *microfabrication technologies*, or *micromachining*. For example, the three-dimensional microstructures can be produced by removing part of the base material by a physical or chemical etching process, whereas thin-film deposition techniques are used to build layers of materials on the base materials. We will learn these microfabrication processes and micromanufacturing technologies in detail in, respectively, Chapters 8 and 9.

Current micromanufacturing processes involve a significant number of microfabrication processes that were developed for the microelectronics industry in the last 50 years. Microfabrication processing is thus an important part of microsystems design, manufacture, packaging, and assembly.

Many would attribute the origin of modern-day microfabrication to the invention of transistors by W. Schockley, J. Bardeen, and W. H. Brattain in 1947. Indeed, microfabrication technology is inseparable from the IC fabrication technology that is used to produce microelectronics. The IC concept was first evolved from the production of the monolithic circuit at RCA in 1955 after the invention of transistors. The first IC was produced three years later by Jack Kilby of Texas Instruments. It was in the same year that Robert Noyce of Fairchild Semiconductors produced the first planar silicon-based IC. Today, the next generation of IC, that is, the ULSI (ultra-large-system integration), can contain 10 million transistors and capacitors on a typical chip of size that is smaller than a fingernail.

The term *micromachining* first appeared in the public literature in 1982, although some of its key processes were in existence long before. For example, a key fabrication process known as *isotropic etching* of silicon was first used in 1960, and the improved *anisotropic etching* was invented in 1967.

1.4 MICROSYSTEMS AND MICROELECTRONICS

It is a well-recognized fact that microelectronics is one of the most influential technologies of the twentieth century. The boom of the MEMS industry in recent years would not have been possible without the maturity of microelectronic technology. Indeed, many engineers and scientists in today's MEMS industry are veterans of the microelectronics industry, as the two technologies do share many common fabrication technologies. However, overemphasis on the similarity of the two technologies is not only inaccurate, but it can also seriously hinder further advances of microsystems development. We will notice that there are significant differences in the design, packaging, and assembly of microsystems from that of ICs and microelectronics. It is essential that engineers recognize these differences and develop the necessary methodologies and technologies accordingly. Table 1.1 summarizes the similarities and differences between the two technologies.

We may observe from Table 1.1 that there are indeed sufficient differences between the two technologies. Some of the more significant differences between these two technologies are as follows:

1. Microsystems involve more different materials than microelectronics. Other than the common material of silicon, other materials such as quartz and GaAs are used as substrates in microsystems. Polymers and metallic materials are common in microsystems produced by LIGA processes. Packaging materials of microsystems include glasses, plastics, and metals, which are excluded in microelectronics.
2. Microsystems are designed to perform a greater variety of functions than ICs. The latter are limited to specific electrical functions.

TABLE 1.1. Comparison of Microsystems and Microelectronics

Microsystems and MEMS (Silicon Based)	Integrated Circuits
Complex three-dimensional structures	Primarily 2-dimensional structures
Packaged products may involve moving components, access to light beams, and sealing fluids and chemicals	Stationary structure once they are packaged
Perform a variety of specific biological, chemical, electromechanical, and optical functions	Transmit electricity for specific electrical functions
Delicate components required to interface with working media	Delicate dies are protected from contacting media
Use single-crystal silicon dies, silicon compounds, ceramics, and other materials, e.g., quartz, polymers, and metals	Use single-crystal silicon dies, silicon compounds, ceramics, and plastics
Many more components to be packaged and assembled	Fewer components to be packaged and assembled
Lack of engineering design methodology and standards	Mature design methodologies
Simpler patterns over the substrates but require integration with complex electrical circuits for signal transduction	Complex patterns with high-density electrical circuitry over substrates
No industrial standard to follow in design, material selections, fabrication processes, and packaging and assembly	Industrial standards available
Most are in low-volume batch production on customer need bases	Mass production
Available manufacturing techniques of bulk micromanufacturing, surface micromachining, and the LIGA process	Manufacturing techniques are proven and well documented
Packaging and assembly techniques are at infant stage of development	Packaging and assembly techniques are well established
Lack of testing and measurement techniques and tools	Well-documented techniques available
Involve all disciplines of science and engineering	Primarily involve electrical and chemical engineering

3. Many microsystems involve moving parts such as microvalves, pumps, and gears. Many require fluid flow through the systems such as in biosensors and analytic systems. Micro-optical systems need to provide input/output (I/O) ports for light beams. Integrated circuits and microelectronics, on the other hand, do not have any moving component or access for lights or fluids.

4. Integrated circuits are primarily two-dimensional in structure and are confined to the silicon die surface, whereas most microsystems involve complicated geometry in three-dimensions. Mechanical engineering design is thus an essential part in the product development of microsystems.
5. The core elements in ICs are shielded by passivation materials from the surroundings once they are packaged. The sensing elements and many core elements in microsystems, however, are required to be in contact with working media, which creates many technical problems in design and packaging.
6. Manufacturing and packaging of ICs and microelectronics are mature technologies with well-documented industry standards. The production of microsystems, on the other hand, is far from being at that level of maturity. There are generally three distinct manufacturing techniques, as will be described in Chapter 9. Because of the great variety of structural and functional aspects in microsystems, the packaging and assembly of these products remain in the infant stage at the present time.

The slow advance in the development of microsystems technology is mainly attributed to the complex nature of these systems. As we will learn from Section 1.5, there are many science and engineering disciplines involved in the design, manufacture, and packaging of microsystems.

1.5 MULTIDISCIPLINARY NATURE OF MICROSYSTEMS DESIGN AND MANUFACTURE

Despite the fact that micromanufacturing has evolved from IC fabrication technologies, there are several other science and engineering disciplines involved in today's microsystems design and manufacturing. Figure 1.14 illustrates the applications of principles of natural science and several engineering disciplines in this process.

With reference to Figure 1.14, natural science is deeply involved in the following areas:

1. Electrochemistry is widely used in electrolysis by ionizing substances in some micromanufacturing processes. Electrochemical processes are also used in the design of chemical sensors. More detailed description will be given in Chapters 2 and 3.
2. Electrohydrodynamics principles are used as the driving mechanisms in fluid flows in microchannels and conduits such as in capillary fluid flows, as will be described in Chapters 2, 5, and 10.
3. Molecular biology is intimately involved in the design and manufacture of biosensors and biomedical equipment, as will be presented in Chapter 2. Most of the basic molecular biology principles are used in the development of nanotechnology in areas such as self-replication and assemblies, as will be elaborated in Chapter 12.
4. Plasma physics involves the production and supply of ionized gases with high energy. It is required for etching and depositions in many microfabrication processes. The generation of plasma will be covered in Chapter 3, whereas the application of plasma in microfabrication will be described in Chapter 8.

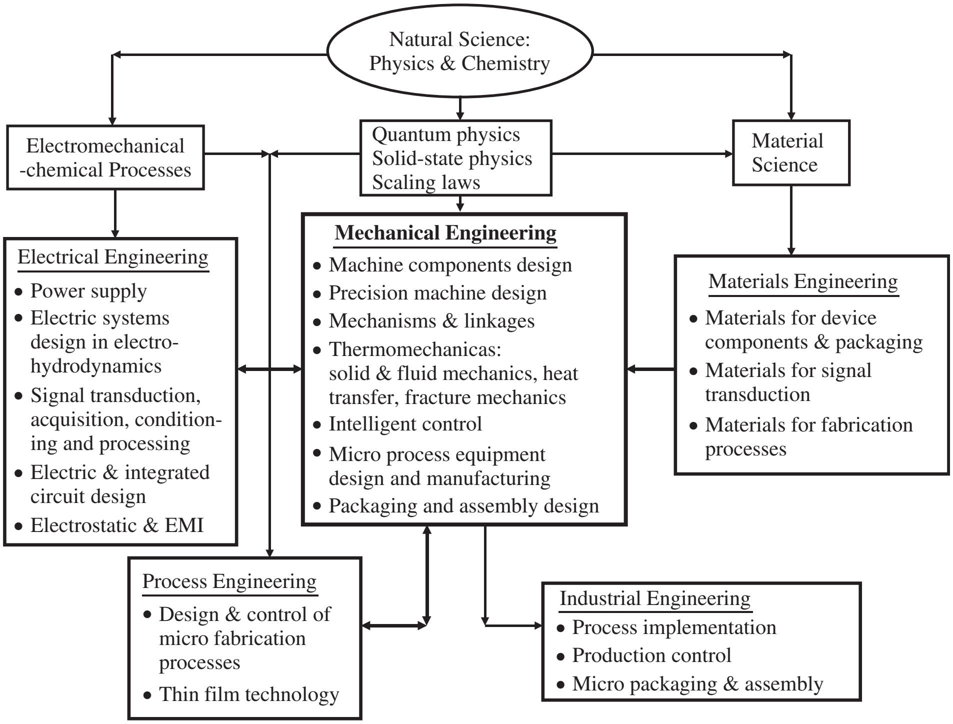


Figure 1.14. Principal science and engineering disciplines involved in microsystems design and manufacture.

5. Scaling laws provide engineers with a sense for the scaling down of physical quantities involved in the design of microdevices. We will realize from Chapter 6 that not all physical quantities can be scaled down favorably.
6. Quantum physics is used as the basis for modeling certain physical behaviors of materials and substances in microscales, as will be described for microfluid flows and heat transportation in solids in Chapter 12.
7. Molecular physics provides many useful models in the description of materials at micro- and nanoscales as well as the alteration of material properties and characteristics used in microsystems, as will be described in Chapters 3, 7, and 12. Molecular dynamics theories are the principal modeling tool for describing mechanical behavior of materials at the nanoscale.

Five engineering disciplines are involved in microsystems design, manufacture, and packaging, as described below:

1. Mechanical engineering principles are used primarily in the design of microsystems structures and the packaging of the components. These tasks involve many aspects of design analyses as indicated in the central box in Figure 1.14. Intelligent

control of microsystems has not been well developed, but it is an essential part of *micromechatronics systems,* which are defined as intelligent microelectromechanical systems.

2. Electrical engineering involves electrical power supply and the functional control and signal processing circuits design. For the integrated microsystems, for example, "laboratory-on-the-chip," the IC and microelectronics circuitry that integrates microelectronics and microsystems makes electrical engineering a major factor in the design and manufacturing processes.
3. Chemical engineering is an essential component in microfabrication and micromanufacturing, as will be described in Chapters 8 and 9. Almost all such processes involve chemical reactions. Some of the microdevice packaging techniques also rely on special chemical reactions, as will be described in Chapter 11.
4. Materials engineering offers design engineers with the selection and characterization of available materials that are amenable to microfabrication and micromanufacturing as well as packaging. Theories of molecular physics are often used in the design of the material's characteristics, such as doping the semiconducting materials to change the electrical resistivity of the material. Materials engineering plays a key role in the development of chemical, biological, and optical sensors, as will be described in Chapter 2.
5. Industrial engineering relates to the assembly and production of microsystems. Optimum design of microfabrication processes and control with required equipment and facility is essential in microsystems production. Much MEMS production falls into the category of medium volume with medium variety, and flexible micromanufacturing systems appear to be both beneficial and desirable.

1.6 MICROSYSTEMS AND MINIATURIZATION

It is fair to say that microsystems, as we have defined in Section 1.1, are a major step toward the ultimate miniaturization of machines and devices, such as dust-size computers and needle-tip-size robots that have fascinated many futurists in their seemingly science fiction articles and books. The current microsystems technology, though at a relative early stage, has already set the tone for the development of device systems at the nanoscale for this new century. [A nanometer (nm) is 10^{-9} meter.] The maturity of nanotechnology will certainly result in the realization of much of the superminiaturized machinery that engineers and scientists have fantasized at the present time.

According to *Webster's Dictionary*, the word *miniature* means a copy on a much-reduced scale. In essence, miniaturization is an art that substantially reduces the size of the original object yet retains the characteristics of the original (and more) on the reduced copy. The need for miniaturization has become more prominent than ever in recent decades, as engineering systems and devices have become more and more complex and sophisticated. The benefits of having smaller components and hence a device or machine with enhanced capabilities and functionalities are obvious from engineering perspectives:

- Smaller systems tend to move more quickly than larger systems because of smaller mass and thus low mechanical inertia.
- Likewise, smaller systems react to change of thermal conditions much rapidly than larger systems because of low thermal inertia. It is therefore more effective in actuation by thermal forces.
- Smaller systems do not produce significant overall thermal distortion because of their small sizes.
- The minute sizes of small devices encounter fewer problems in vibration because resonant vibration of a system is inversely proportional to the mass. Smaller systems with lower masses have much higher natural frequencies than those expected from most machines and devices in operation. Silicon-based miniature condenser microphones as described in Chapter 2 are virtually free from resonant diaphragm vibration for this reason.
- In addition to the more accurate performance of smaller systems, their minute sizes make them particularly suitable for applications in medicine and surgery and microelectronics assemblies in which miniaturized tools are necessary.
- Miniaturization is also desirable in satellites and spacecraft engineering to satisfy the prime concerns about high precision and payload size.
- The high accuracy of miniaturized systems in motion and dimensional stability makes them particularly suitable for telecommunication systems.

The process of miniaturizing engineering systems has been an ongoing effort by engineers. We have witnessed many of the results of miniaturization in consumer products with much better performance but much reduced size. Such products include hair dryers, cameras, radios, and telephone sets. We will see from the following examples and appreciate how these efforts have produced even more staggering results in other fundamentally important engineering products in the last 50 years. There is no doubt that with the rapid development of microsystems technologies, such process will be accelerated at an even more spectacular rate.

Perhaps the foremost important miniaturization began with the development of ICs in the mid-1950s. As described in Section 1.3, a ULSI of the size of a small fingernail can contain 10 million transistors. Microprocessors of similar size can now perform over 300 millions operations per second. A leading microprocessor manufacturer in the United States reported its success in early 2007 in producing transistors that have the size of 45 nm, which is equivalent to having 2000 wires in the space of a human hair.

The advances in the IC and microprocessor technologies have led to a spectacular level of miniaturization of complex digital electronics computers. Two engineers, J. Presper Eckert and John Mauchly, publicly demonstrated the first general-purpose electronic digital computer called ENIAC (Electronic Numerical Integrator and Calculator) in 1946 at the Moore School of Electrical Engineering at the University of Pennsylvania. The U.S. Army during World War II originally funded this project. As shown in Figure 1.15, the U-shaped computer was 80 ft long by 8.5 ft high and several feet wide. Each of

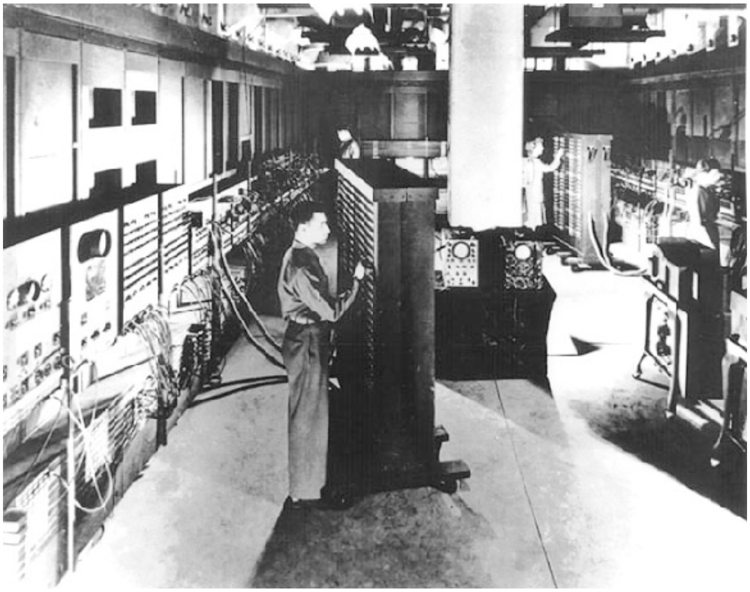


Figure 1.15. The ENIAC digital computer in 1947. (Used by permission of the University of Pennsylvania's School of Engineering and Applied Science, formerly known as the Moore School of Electrical Engineering.)

the twenty 10-digit accumulators was 2 ft long. In total, ENIAC had 18,000 vacuum tubes.

At the time of the ENIAC fiftieth anniversary celebration, Dr. Van der Spiegel worked with a group of students at the same university to reduce the original ENIAC to the size of a tiny chip with equivalent functional power (shown in Figure 1.16) (Van der Spiegel et al., 1998).

In sharp contrast to ENIAC, a typical notebook or laptop computer, shown in Figure 1.17, is only about 14 in. long by 10 in. wide by 1 in. thick. In size, ENIAC, estimated at about 4000 ft^3, was more than five orders of magnitude bigger than laptop computers today, but the latter have a computational speed that is six to eight orders of magnitudes faster than ENIAC. This staggering miniaturization took place in just about 50 years!

The microfabrication technology that evolved from IC fabrications in the last two decades has made machine components in sizes of micrometers and submicrometers possible. Many of these devices and components have been shown in the foregoing sections. While most sensors and actuating components use silicon as primary material, other materials such as nickel and ceramics have been used. High-aspect-ratio microstructures (the *aspect ratio* is the ratio of the dimensions in the height to those of the surface) have been successfully manufactured by the LIGA process, as shown in

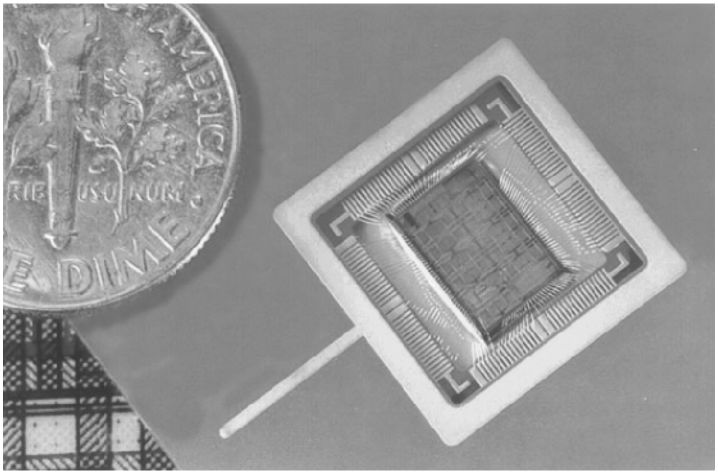


Figure 1.16. The “miniaturized” ENIAC. (Used by permission of the University of Pennsylvania’s School of Engineering and Applied Science, formerly known as the Moore School of Electrical Engineering.)

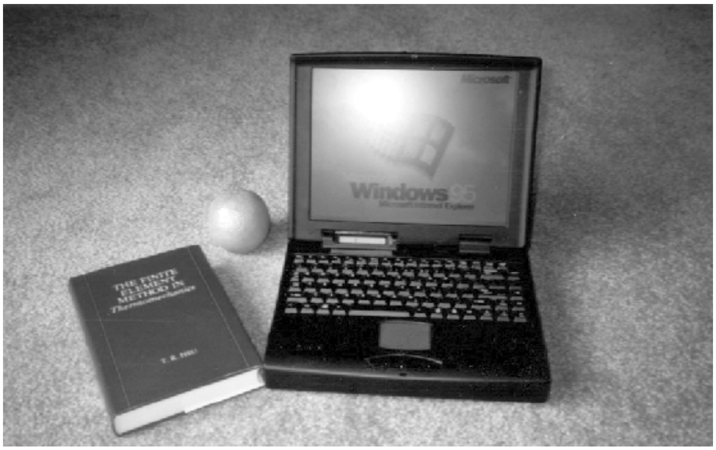


Figure 1.17. Laptop computer as of 2000.

Figures 1.9–1.11. This special micromanufacturing process will be described in detail in Chapter 9. The broader use of materials along with the possibility of producing MEMS with high aspect ratio by the LIGA process has prompted the production of miniaturized machines.

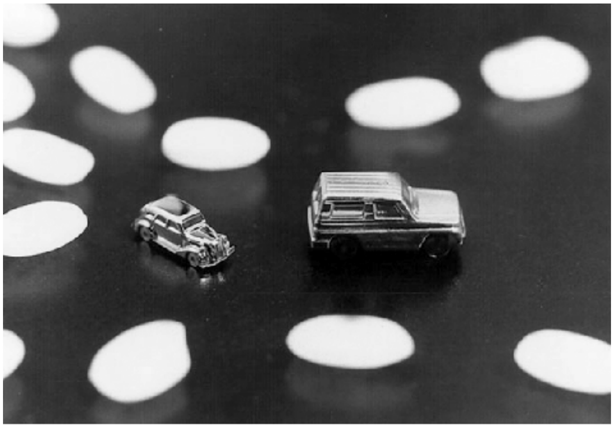
Another driving force for miniaturizing industrial products is the strong market demand for smaller, intelligent, robust, and multifunctional consumer products. Figure 1.18 illustrates the evolution of mobile personal telecommunication equipment. On the left is

Figure 1.18. Evolution of mobile telecommunication devices.

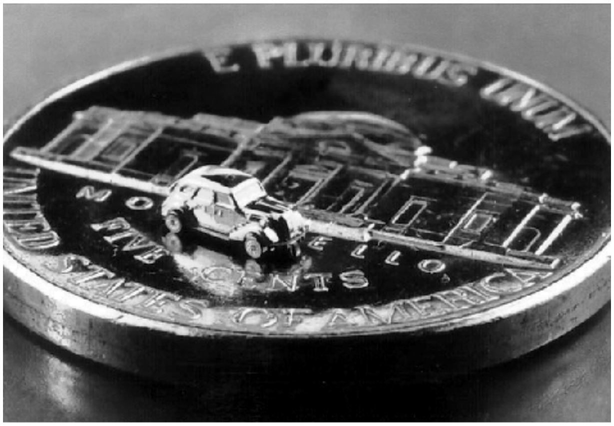
the mobile telephone set at its debut 15 years ago. It was a breakthrough in telecommunication technology at that time, as for the first time consumers could use a cordless hand-held device to transceive voice messages almost everywhere in the world. The popularity of mobile phones has led to a speedy evolution to their current state-of-the-art of smaller but more versatile telephone sets and powerful personal digital assistants (PDAs), as shown in the figure. Although the reduction in size of these telecommunication devices has not been as spectacular as in digital computers, the functions that they can perform are truly spectacular; a current mobile telephone, which is about one-quarter of the size of the original sets, can be used, in addition to transceive voices, as a clock, a calendar, a video camera, and an instant positioning device with the use of the global positioning system (GPS) through satellites. The PDA devices combine computing, telephone/fax, Internet, and networking features. A typical PDA can function as a cellular phone, fax sender, Web browser, and personal organizer. Unlike laptop computers, most PDAs began as pen based, using a stylus rather than a keyboard for input. This means that they also incorporated handwriting recognition features. Some PDAs can also react to voice input by using voice recognition technologies. Most PDAs of today are available in either a stylus or keyboard version.

We may quickly realize that the only solution to produce these smaller, intelligent, and multifunctional products such as mobile telephones and PDAs is to pack many miniature function components into the same device.

Another spectacular micromachine is the microcars that were produced by the Denso Corporation in Japan. Figure 1.19 shows cars the size of rice grains. The smaller car shown in the figure weighs 33 mg. The overall dimensions are 4.785 mm long by 1.73 mm wide by 1.736 mm high. The body is made of nonelectrolysis nickel plating. The nickel film is 30 μm thick. These two cars were fabricated using microprecision machining with semiconductor processes. The electrical motor that drives the cars uses magnetic induction, with a rotor of 0.6 mm in diameter. Detailed design methodology for these cars can be found in an article by Teshigahara et al. (1995).



(*a*)



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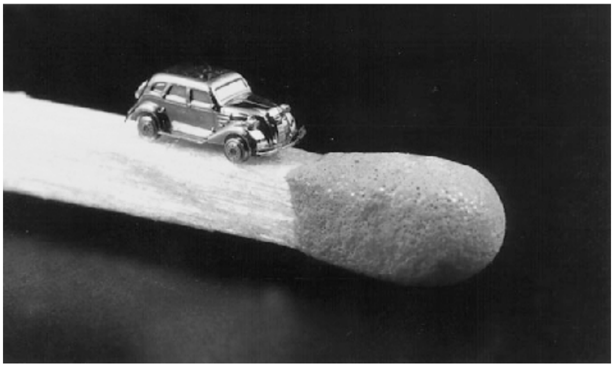

(*c*)

Figure 1.19. Miniature electric cars: (*a*) comparing with the size of rice grains; (*b*) comparing with the size of an American 5c coin; (*c*) miniature car resting near the of matchstick. (Courtesy of Denso Research Laboratories, Denso Corporation, Aichi, Japan.)

1.7 APPLICATION OF MICROSYSTEMS IN AUTOMOTIVE INDUSTRY

The MEMS and microsystems products have become increasingly dominant in every aspect of the marketplace as technologies for microfabrication and miniaturization continue to be developed. At the present time, two major commercial markets for these products are (1) the information technology industries involving the productions of inkjet printer heads and read/write devices in data storage and (2) the automotive industry. We will focus our attention to the latter due to the high variety of products.

The automotive industry has been the major user of MEMS technology in the last two decades because of the size of its market. A 1991 report indicated that the industry had a production of 8 million vehicles per year with 6 million of these in the United States (Sulouff, 1991). The number of vehicles produced in the United States rose to 17 million in 2005 (National Geographic, 2005). The primary motivation for adopting MEMS and microsystems in automobiles is to make automobiles safer and more comfortable for riders and to meet the high fuel efficiencies and low emissions standards required by governments. In all, the widespread use of these products can indeed make the automobile "smarter" for consumers' needs. The term *smart cars* was first introduced in the cover story of a special issue of a trade magazine (Smart Cars, 1988). Many of the seemingly fictitious predictions of the intelligent functions of a smart car are in place in today's vehicles.

Smart vehicles are built on the extensive use of sensors and actuators. Various kinds of sensors are used to detect the environment or road conditions, and the actuators are used to execute whatever actions are required to deal with these conditions. Microsensors and actuators allow automobile makers to use smaller devices, and thus more of them, to cope with the situation in much more effective ways. Comprehensive summaries on the use of sensors and actuators are available in an early report (Paulsen and Giachino, 1989). Sensors of various kinds are extensively used in automobile engines, as illustrated in Figure 1.20. Figure 1.21 illustrates the application of pressure sensors in an automobile.

The design and production of automobiles satisfying the above expectations present a major challenge to engineers as these vehicles are expected to perform in extreme environmental conditions as outlined in several reports (Giachino and Miree, 1995; Chiou, 1999). Table 1.2 presents some of these stringent requirements for endurance tests for MEMS components used in the automotive industry.

In addition to the stringent endurance testing conditions for sensors and actuators presented in Table 1.2, they are expected to perform in extremely harsh environmental conditions. Design conditions include a temperature range of -40 to $+125^\circ$ C and a dynamic loading up to 50g (MacDonald, 1990). Table 1.2 presents some of the endurance testing conditions for pressure sensors (Chiou, 1999). The pressure range for automobiles extends from 100 kPa for a manifold absolute pressure (MAP) to 10 MPa for brake pressure sensors.

Applications of microsystems in automobiles can be categorized into the following four major areas: (1) safety, (2) engine and power train, (3) comfort and convenience, and (4) vehicle diagnostics and health monitoring.

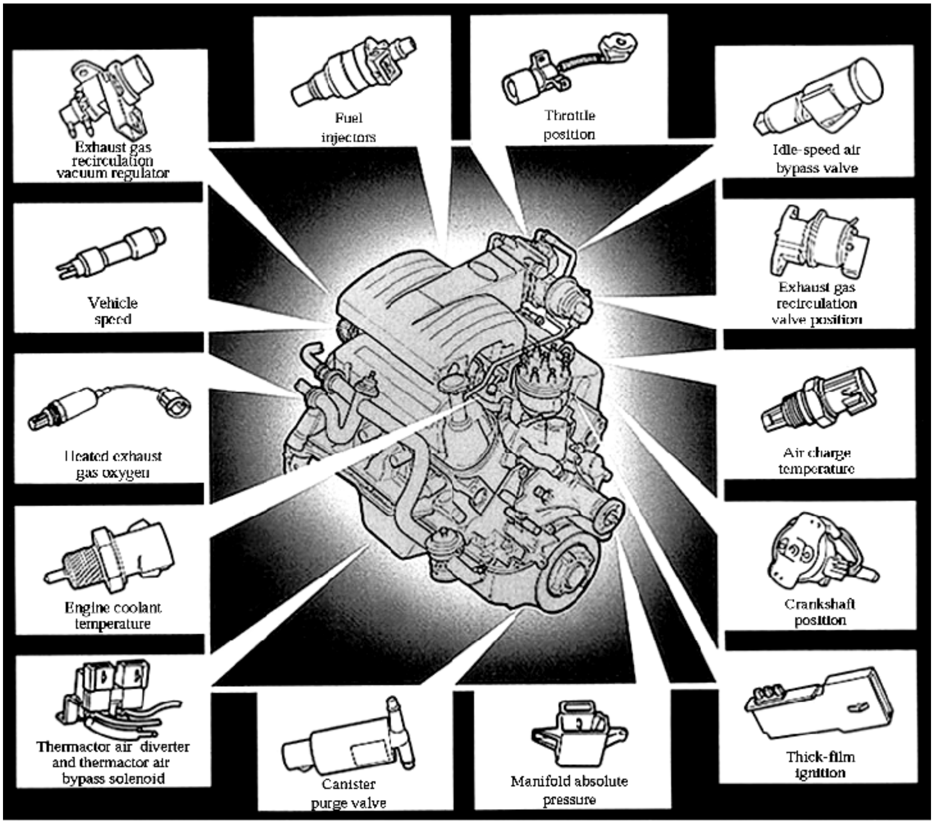

Figure 1.20. Sensors in an automobile engine and powertrain. [Reproduced from Paulsen and Giachino (1989) with permission.]

1.7.1 Safety

- An airbag deployment system is introduced in automobiles to protect the driver and passengers from injury in the event of serious vehicle collision. The system uses microaccelerometers or micro–inertia sensors similar to those illustrated in Figures 1.6 and 1.8.
- An antilock braking system using position sensors allows the driver to steer the vehicle with ceased wheels while braking.
- Suspension systems, using displacement, position and pressure sensors, and microvalves, mitigate violent vibrations of the vehicle that cause structural damages and discomfort to the riders.
- Object avoidance using pressure and displacement sensors allows the driver to detect obstructions along the path of the vehicle.
- An automatic navigation system using microgyroscope and GPS can navigate the moving vehicle in hazardous and rough terrain.

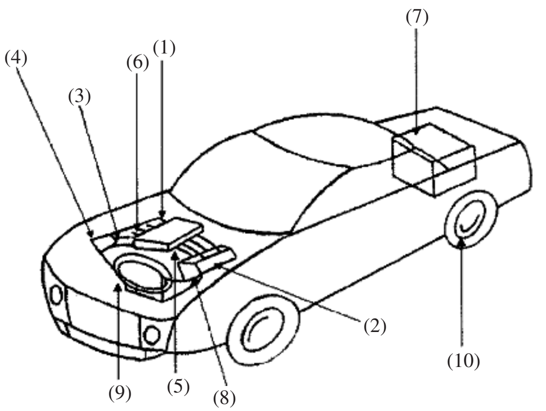

Figure 1.21. Pressure sensors in automotive applications. [Reproduced from Chiou (1999) with permission.]

TABLE 1.2. Typical Durability Requirements

Tests	Conditions	Duration
High-temperature bias	100°C, 5 V	1000 h
Thermal shock	−40 to 150°C	1000 cycles
Temperature and humidity	85°C and 85% relative humidity (RH) with and without bias	1000 h
Pressure, power, and temperature cycles	20 kPa to atmospheric pressure, 5 V, −40 to 150°C	3000 h
Hot storage	150°C	1000 h
Cold storage	−40°C	1000 h
Pressure cycling	700 kPa to atmospheric pressure	2 million cycles
Overpressure	2 × maximum operating pressure	
Vibration	2g to 40g, frequency sweep, depending on locations	30 + hours in each axis
Shock	50g with 10-ms pulses	100 times in three planes
Fluid/media compatibility	Air, water, corrosive water, gasoline, methanol, ethanol, diesel fuel, engine oil, nitric and sulfuric acids	Varies with applications

Source: Chiou, 1999.

1.7.2 Engine and Power Trains

Various sensors have been used in engines of modern automobiles, as illustrated in Figure 1.20 (Paulsen and Giachino, 1989). Following are a few of these sensors:

- Manifold control with pressure sensors
- Airflow control
- Exhaust gas analysis and control (see Figure 1.21)
- Crankshaft position
- Fuel pump pressure and fuel injection control
- Transmission force and pressure control
- Engine knock detection for higher power output (Keneyasu et al., 1995)

The MAP was one of the first microsensors adopted by the automotive industry, in the early 1980s. It measures MAP along with the engine speed in rpm to determine the ignition advance. This ignition timing with optimum air–fuel ratio can optimize the power performance of the engine with low emissions. Early designs of MAP sensors were called SCAP (silicon capacitive absolute pressure) sensors. A typical SCAP is shown in Figure 1.22 (Paulsen and Giachino, 1989). The manifold gas enters the sensor at the tubular intake, shown at the top of Figures 1.22*a* and *b*. The intake gas exerts a pressure to a silicon diaphragm, which acts as one of the two electrodes in the chamber, as shown in Figure 1.22*c*. The deflection of the diaphragm from the applied pressure results in a change in the gap between the two electrodes. The applied pressure can be correlated to the change of the capacitance of the electrodes in the capacitor. Appropriate bridge circuits, such as shown in Figure 2.11, are used to convert the change of the capacitance signal output to electric voltages. Figure 1.22*d* shows the relative size of the SCAP unit.

The capacitive pressure sensors have two major shortcomings: bulky size and nonlinear voltage output with respect to the input pressure (Figure 2.13). Consequently, piezoresistive transducer (PRT) pressure sensors that provide DC voltage output that is proportional to the applied pressure have gradually replaced them. The use of piezoresistives as the signal transducer has significantly reduced the size of the sensors.

1.7.3 Comfort and Convenience

- Seat control (displacement sensors and microvalves)
- Rider comfort (sensors for air quality, airflow, temperature, and humidity controls)
- Security (remote status monitoring and access control sensors)
- Sensors for defogging windshields
- Satellite navigation sensors

1.7.4 Vehicle Diagnostics and Health Monitoring

- Engine coolant temperature and quality
- Engine oil pressure, level, and quality
- Tire pressure (Figure 1.21)
- Brake oil pressure

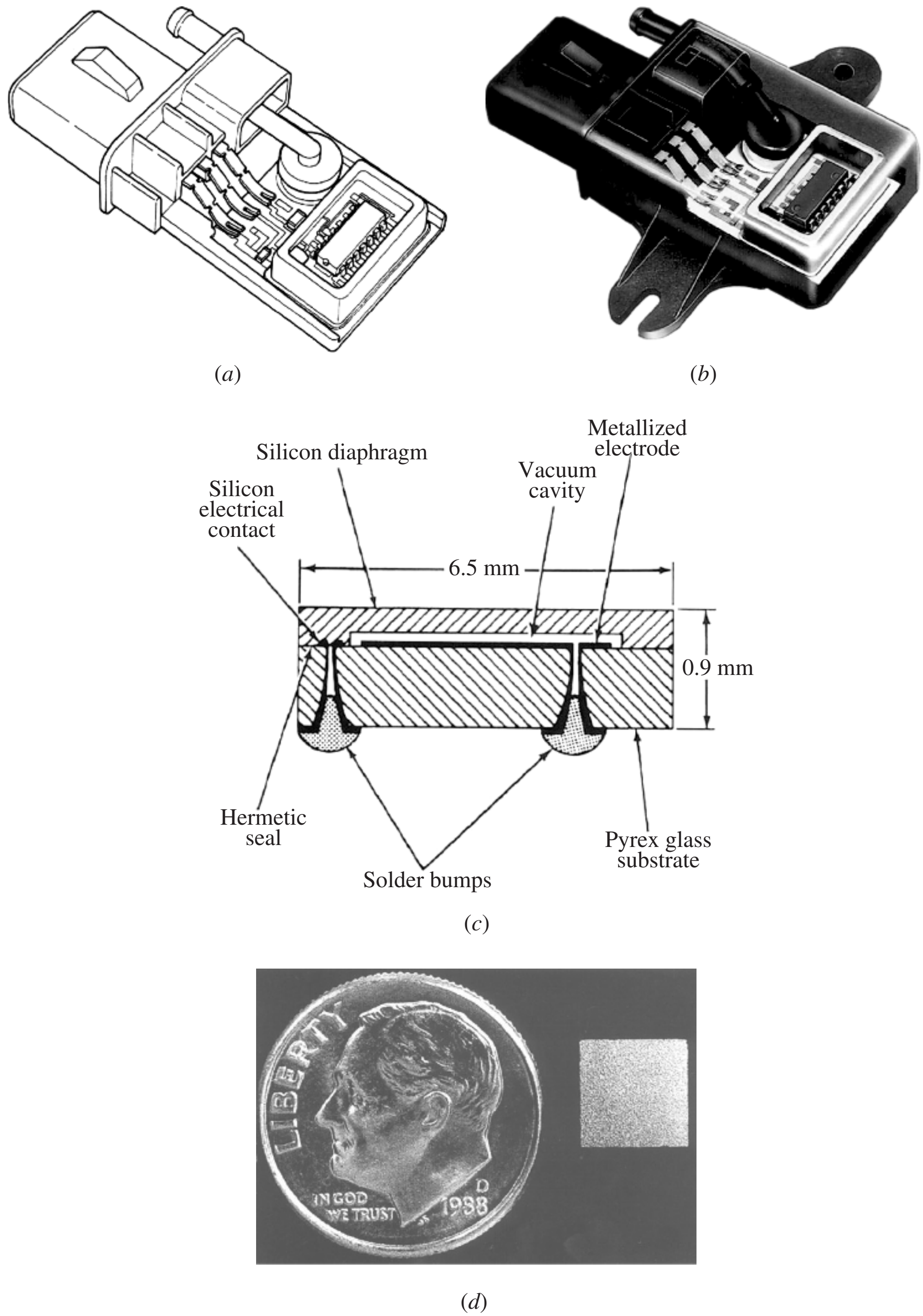

Figure 1.22. Silicon capacitive manifold absolute pressure sensor. (Courtesy of Ford Motor Company.)

- Transmission fluid (Figure 1.21)
- Fuel pressure (Figure 1.21)

1.7.5 Future Automotive Applications

A report (Powers and Nicastri, 1999) indicated that there were 52 million vehicles produced worldwide in 1996, and this number was expected to increase to 65 million by year 2005 because of the growth of the global economy. Consumer expectation on the safety, comfort, and performance of cars will continue to grow. There is every reason to believe that vehicles in the future will contain even more microprocessors with many more microsensors and actuators (Figure 1.23) to be truly smart. Figure 1.24 illustrates the sensors; most of them will be in the microscale range in future vehicles.

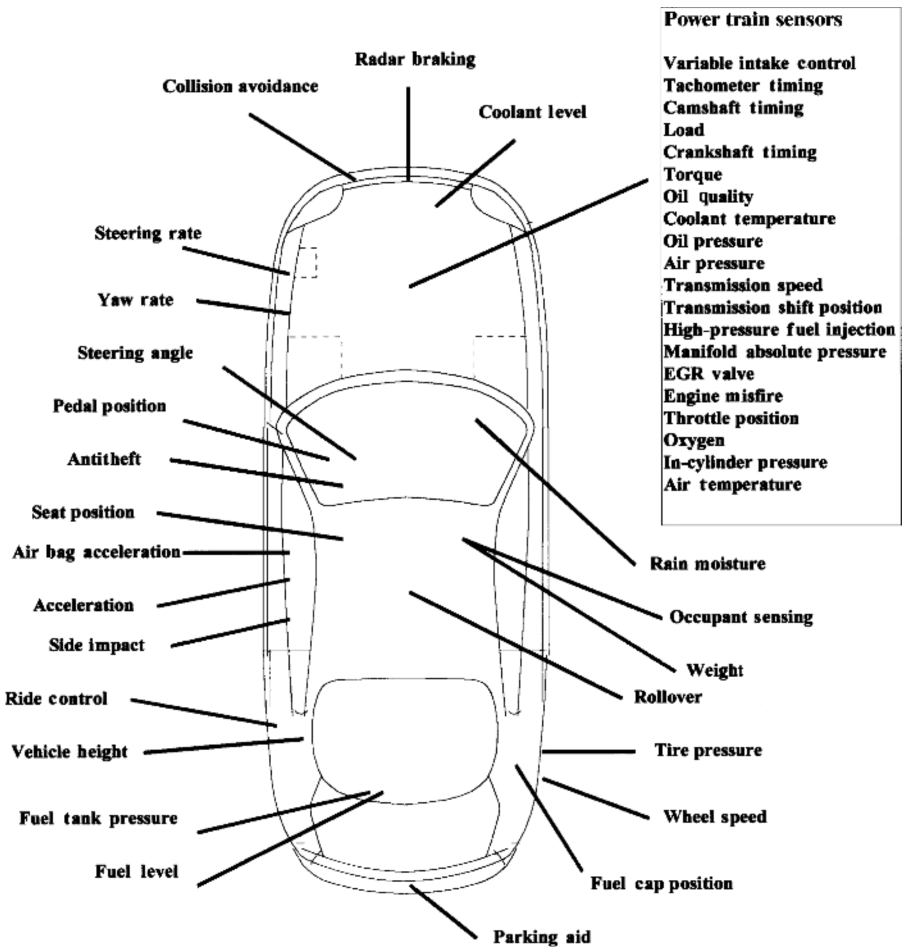

Figure 1.23. Microprocessor control components for future vehicles. (Courtesy of Ford Motor.)

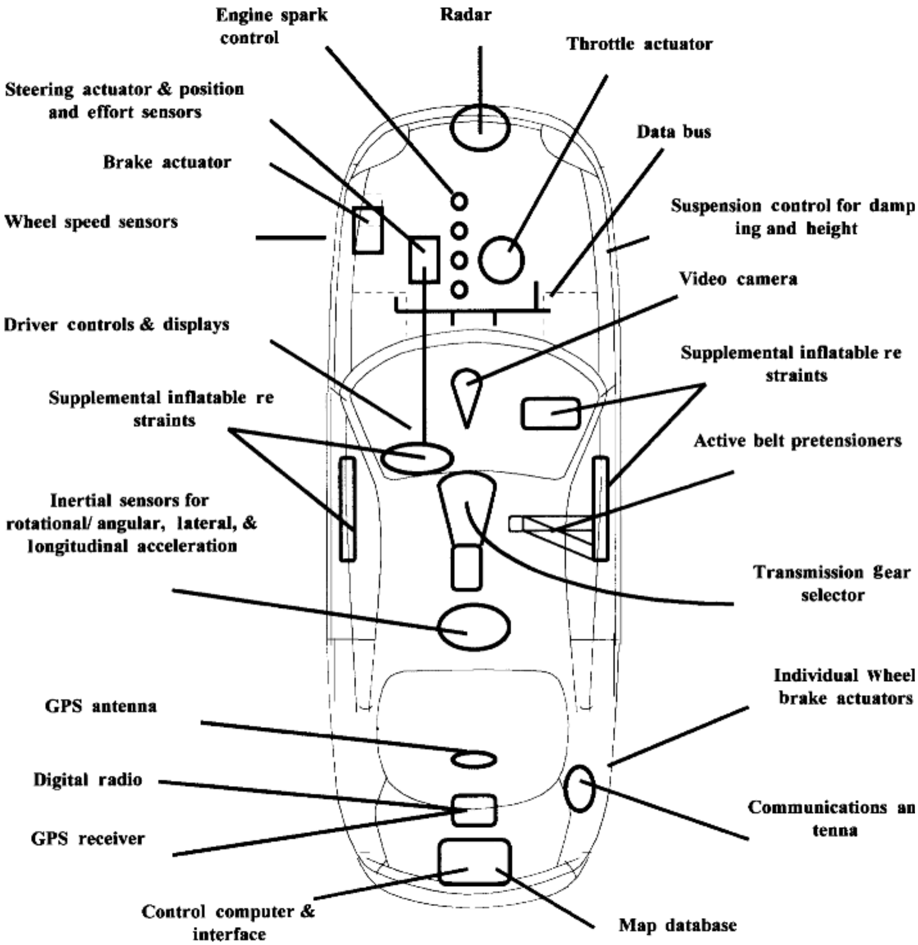

Figure 1.24. Sensors for future vehicles. (Courtesy of Ford Motor.)

1.8 APPLICATION OF MICROSYSTEMS IN OTHER INDUSTRIES

Other commercial applications of MEMS such as biomedical and genetic engineering are emerging at an astounding rate in recent years. We will offer applications of MEMS and microsystems in five industrial sectors.

1.8.1 Application in Health Care industry

- Disposable blood pressure transducer (DPT): lifetime 24–72 hours; approximate annual production 17 million units per year, unit price <\$10
- Intrauterine pressure sensors (IUPs): to monitor pressure during child delivery; current market about 1 million units per year

- Angioplasty pressure sensors: to monitor pressure inside a balloon inserted in a blood vessel; current market about 500,000 units per year
- Infusion pump pressure sensors: to control the flow of intravenous fluids and permit several drugs to be mixed into one flow channel; approximate market size about 200,000 units per year
- Other products:

  Diagnostics and analytical systems, such as capillary electrophoresis systems (Section 2.2.2 and Chapter 10)

  Human care support systems

  Catheter tip pressure sensors

  Sphygmomanometers

  Respirators

  Lung capacity meters

  Barometric correction of instrumentation

  Medical process monitoring (e.g., drug production by growth of bacteria)

  Kidney dialysis equipment

1.8.2 Application in Aerospace Industry

- Cockpit instrumentation

  Pressure sensors for oil, fuel, transmission, and hydraulic systems

  Air speed measurement

  Altimeters
- Safety devices (e.g., sensors and actuators for ejection seat controls)
- Wind tunnel instrumentation (e.g., shear stress sensors)
- Sensors for fuel efficiency and safety
- Microgyroscope for navigation and stability control
- Microsatellites

A comprehensive summary of possible uses of MEMS and microsystems in space hardware in the near term (less than 10 years) is presented below (Helvajian and Janson, 1999):

- Command and control systems with MEMtronics for ultraradiation and temperature-insensitive digital logic and on-chip thermal switches for latch-up and reset
- Inertial guidance systems with microgyroscopes, accelerometers, and fiber-optic gyros
- Attitude determination and control systems with micro sun and Earth sensors, magnetometers, and thrusters

- Power systems with MEMtronic blocking diodes, switches for active solar cell array reconfiguration, and electric generators
- Propulsion systems with micro–pressure sensors, chemical sensors for leak detection, arrays of single-shot thrusters, continuous microthrusters, and pulsed microthrusters
- Thermal control systems with micro–heat pipes, radiators, and thermal switches
- Communications and radar systems with very high bandwidth, low-resistance radio frequency switches, micromirrors, and optics for laser communications, micro–variable capacitors, inductors, and oscillators
- Space environment sensors with micromagnetometers and gravity-gradient monitors (nano-g accelerometers)

There has been considerable effort as well as progress in recent years in the development of micropropulsion systems that include micropropellants, nozzles, jet engines, and thrusters (Janson et al., 1999). Principal supporting mechanical engineering subjects include microfluid modeling, microcombustion, and rocket science.

1.8.3 Application in Industrial Products

- Manufacturing process sensors: process pressure transmitters (>200,000 units per year)
- Sensors for:

    Hydraulic systems

    Paint spray

    Agricultural irrigations and sprays

    Refrigeration systems

    Heating, ventilation, and air conditioning systems

    Water-level controls

    Telephone cable leak detection

1.8.4 Application in Consumer Products

- Scuba diving watches and computers
- Bicycle computers
- Fitness gears using hydraulics, washers with water-level controls
- Sport shoes with automatic cushioning control
- Digital tire pressure gages
- Vacuum cleaning with automatic adjustment of brush beaters
- Smart toys
- Smart home appliances

1.8.5 Application in Telecommunications

- Optical switching and fiber-optic couplings
- Radio frequency (RF) MEMS in wireless systems (Rebeiz, 2003)
- Tunable resonators

1.9 MARKETS FOR MICROSYSTEMS

As new MEMS and microsystems products have become available, the market for these products has been expanding rapidly. Table 1.3 shows the world market projections to year 1999.

We observe from Table 1.3 that the compound annual growth rate since 1992 is 15.9%. Unit prices continued to drop as volume of production increased.

The MEMS market size takes a dramatic expansion if one follows the definition of MEMS and microsystems products by NEXUS, a European Community that initiated the Network of Excellence in Multifunctional Microsystems. It includes all products that are microstructures in design, including monolithic and hybrid components and silicon-based devices, as well as anything micromachined. The market for established MEMS product between 1996 and 2002 is tabulated in Table 1.4.

NEXUS also offered a market growth of MEMS and microsystems products between 2000 and 2005, as shown in Figure 1.25.

We may observe from Figure 1.25 that information technology (IT) peripherals that include read–write heads for hard disk drives and inkjet printer heads dominate the

TABLE 1.3. Worldwide Silicon-Based Micro Sensor Market

Year	Unit (×1000)	Revenues ($million)	Average Unit Price ($)	Revenue Growth Rate (%)
1989	3026	570.50	188.53	—
1990	5741	744.60	129.70	30.5
1991	6844	851.70	124.44	14.4
1992	7760	925.40	119.25	8.6
1993	8816	977.10	110.83	5.6
1994	10836	1116.20	103.00	14.2
1995	13980	1316.30	94.16	17.9
1996	18127	1564.40	86.30	18.9
1997	23514	1857.60	79.00	18.7
1998	30355	2199.80	72.47	18.4
1999	38792	2593.80	66.86	17.9

Source: Frost & Sullivan Market Intelligence, 1993. (www.frost.com/prod/servlet/frost-home)

TABLE 1.4. Market Growth for Established MEMS Products, 1996–2002

MEMS Products	Year 1996 (10^6 units/revenue in $\$10^6$)	Year 2002 (10^6 units/revenue in $\$10^6$)
HDD heads[a]	530/4500	1500/12000
Inkjet printer heads	100/4400	500/10000
Heart pacemakers	0.5/1000	0.8/3700
In vitro diagnostics	700/450	4000/2800
Hearing aids	4/1150	7/2000
Pressure sensors	115/600	309/1300
Chemical sensors	100/300	400/800
Infrared imagers	0.01/220	04/800
Accelerometers	24/240	90-/430
Gyroscopes	6/150	30/360
Magnetoresistive sensors	15/20	60/60
Microspectrometers	0.006/3	0.15/40
Total	1595/$13,033	6807/$34,290

[a]Read–write heads for hard disk drives.
Source: http://www.wtec.org/loyal/mcc/mems_eu/pages/chapter-6.html.

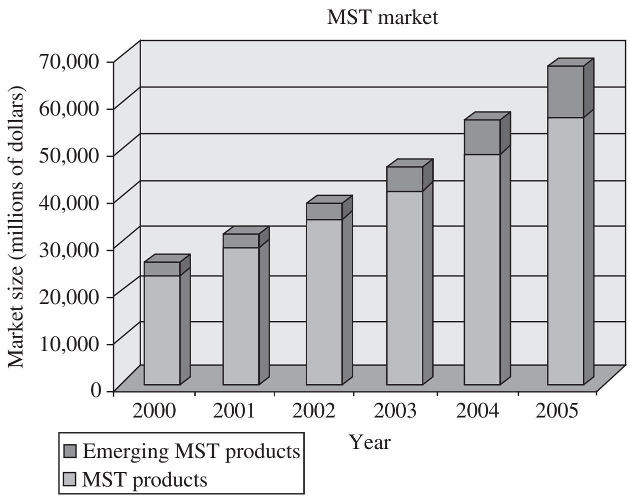

Figure 1.25. Market growth for established and emerging MEMS and microsystems products. (*Source:* Nexus: http://www.smalltimes.com/document_display.cfm?document_id = 3424.)

microsystems (MST) market. Biomedical products such as cardiac pacemakers and hearing aids and other new emerging biomedical products such as lab-on-a-chip analytic systems follow closely the market growth of IT peripherals. Emerging MST products in Figure 1.25 include optical mouse sensors, household appliances, fingerprint sensors, and implantable drug delivery systems. Another potentially significant market for MST products is the flat-panel display for household and industrial applications.

PROBLEMS

Part 1 Multiple Choice

1. The largest market share of MEMS products currently belongs to (a) micropressure sensors, (b) IT peripherals, (c) microaccelerometers.
2. MEMS components range in size (a) from 1 μm to 1 mm, (b) from 1 nm to 1 μm, (c) from 1 mm to 1 cm.
3. One nanometer is (a) 10^{-6} m, (b) 10^{-9} m, (c) 10^{-12} m.
4. When we say a device is mesoscale, we mean the device has the size in the range of (a) 1 μm to 1 mm, (b) 1 nm to 1 μm, (c) 1 mm to 1 cm.
5. The origin of microsystems can be traced back to the invention of (a) transistors, (b) integrated circuits, (c) silicon piezoresistors.
6. A modern integrated circuit may contain (a) 100,000, (b) 1,000,000, (c) 10,000,000 transistors and capacitors.
7. Miniaturization of computers was possible mainly due to (a) better storage systems, (b) replacing vacuum tubes with transistors, (c) the invention of integrated circuits.
8. In general, a microsystem consists of (a) one, (b) two, (c) three components.
9. The microsensor that is commonly used in airbag deployment systems in automobiles is (a) pressure sensor, (b) inertia sensor, (c) chemical sensor.
10. "Lab-on-a-chip" means (a) performing experiments on a chip, (b) integration of microsensors and actuators on a chip, (c) integration of microsystems and microelectronics in a chip.
11. The origin of modern microfabrication technology is (a) invention of transistors, (b) invention of integrated circuits, (c) invention of micromachining.
12. The first significant miniaturization occurred with (a) integrated circuits, (b) laptop computers, (c) mobile telephones.
13. The term *micromachining* first appeared in (a) the 1970s, (b) the 1980s, (c) the 1990s.
14. The term LIGA is (a) a process for micromanufacturing, (b) a microfabrication process, (c) a material treatment process.
15. A typical single ULSI chip may contain (a) one million, (b) ten million, (c) one hundred million transistors.

16. The development of ICs began in (a) the 1960s, (b) the 1970s, (c) the 1950s.

17. The first digital computer, ENIAC, was developed in (a) the 1960s, (b) the 1950s, (c) the 1940s.

18. The *aspect ratio* of a microsystem component is defined as the ratio of (a) the dimension in the height to those of the surface, (b) the dimensions of the surface to that of the height, (c) the dimension in width to that of the length.

19. The market value of microsystems is intimately related to (a) volume demand, (b) special features, (c) performance of the products.

20. The most challenging issue facing microsystems technology is (a) the small size of the products, (b) the lack of practice application, (c) the multidisciplinary nature.

Part 2 Short Problems

1. Give three examples of objects that you recognize to be approximately 1 mm in size.

2. Explain the difference between MEMS and microsystems.

3. What are the most obvious distinctions between microsystems and microelectronics technologies?

4. Why cannot microelectronics technology be adopted in the design and packaging of MEMS and microsystems products?

5. Why cannot traditional manufacturing technologies such as mechanical milling, drilling, and welding be used to produce microsystems?

6. Give at least four distinct advantages of miniaturization of machines and devices.

7. Give two examples of the miniaturization of consumer products that you have observed and appreciated.

8. Ask your doctor to give at least one example of the application of MEMS in biomedicine that offers significant advantage over traditional devices or methods or conduct your own research.

9. Conduct research to configure an airbag deployment system in an automobile.

10. Describe the proper role that you can play in this multidisciplinary microsystems technology with your academic and professional background.