Chapter 2
Technology

INTEGRATED CIRCUITS

Since World War II, system designers have tried to create smaller electronics. Reduction in the size of vacuum tubes progressed slowly as practical limits were encountered. Replacement of vacuum tubes with transistors in the 1960s was a breakthrough in miniaturization. Transistors became smaller, but each transistor was packaged individually, thus mounting large numbers of transistors on a circuit board still resulted in large assembly units. Invention of the integrated circuit overcame that problem by embedding many transistors on a single silicon chip that could be then connected to other components on a circuit board. Integrated circuits accelerated the drive toward transistor miniaturization because, unlike discrete transistors, the connections between transistors could shrink with the transistor. The smaller the transistor and its interconnections, the greater the transistor density (the number of transistors in a given chip area). As chip designers were able to pack more and more transistors onto a single silicon chip, the number of transistors per chip increased nearly a hundred fold each decade (see figure 2-l). As the size of a transistor shrinks it operates faster, leading to faster computation (see figure 2-2).

If this trend continues, sometime after 2000 the smallest feature on an integrated circuit will be about 0.1 micron (1 micron is 1 micrometer or one millionth of a meter). For comparison, today's dynamic random access memory (DRAM) transistor has a smallest feature of about 0.8 micron. The equivalent capacity of a DRAM[1] chip will be over 1 billion bits (1 gigabit). With O.1-micron transistors, microprocessors will contain over 400 million transistors. Industry experts believe that such densities are possible and that there are no fundamental physical limits to prevent achieving them.

The time needed to overcoming engineering and manufacturing problems to reach these high densities is uncertain. Several problems must be overcome to develop high-density chips, including: 1) higher resistance of the minute connections between transistors and within transistors; 2) the tendency of very small transistors (about 0.1 micron) to "leak," rendering them useless; and 3) lack of high-volume manufacturing equipment capable of creating very small features.

Fabrication technologies, especially lithography, have paced the miniaturization of transistors in the past and may ultimately determine the practical economic limits of transistor miniaturization. Fabrication equipment used to make circuits at 0.1 microns must be affordable and capable of sustaining reliable, high-volume production. Electron-beam lithography can now produce features much smaller than 0.1 micron, but is unable to manufacture a sufficient volume of chips to be economical.[2] X-ray lithography and phase-shifted masks (another lithography technique using visible light) are the two most likely contenders for achieving manufacturable O.l-micron transistors. Other prospects include projection electron beam, and projection focused ion beam.

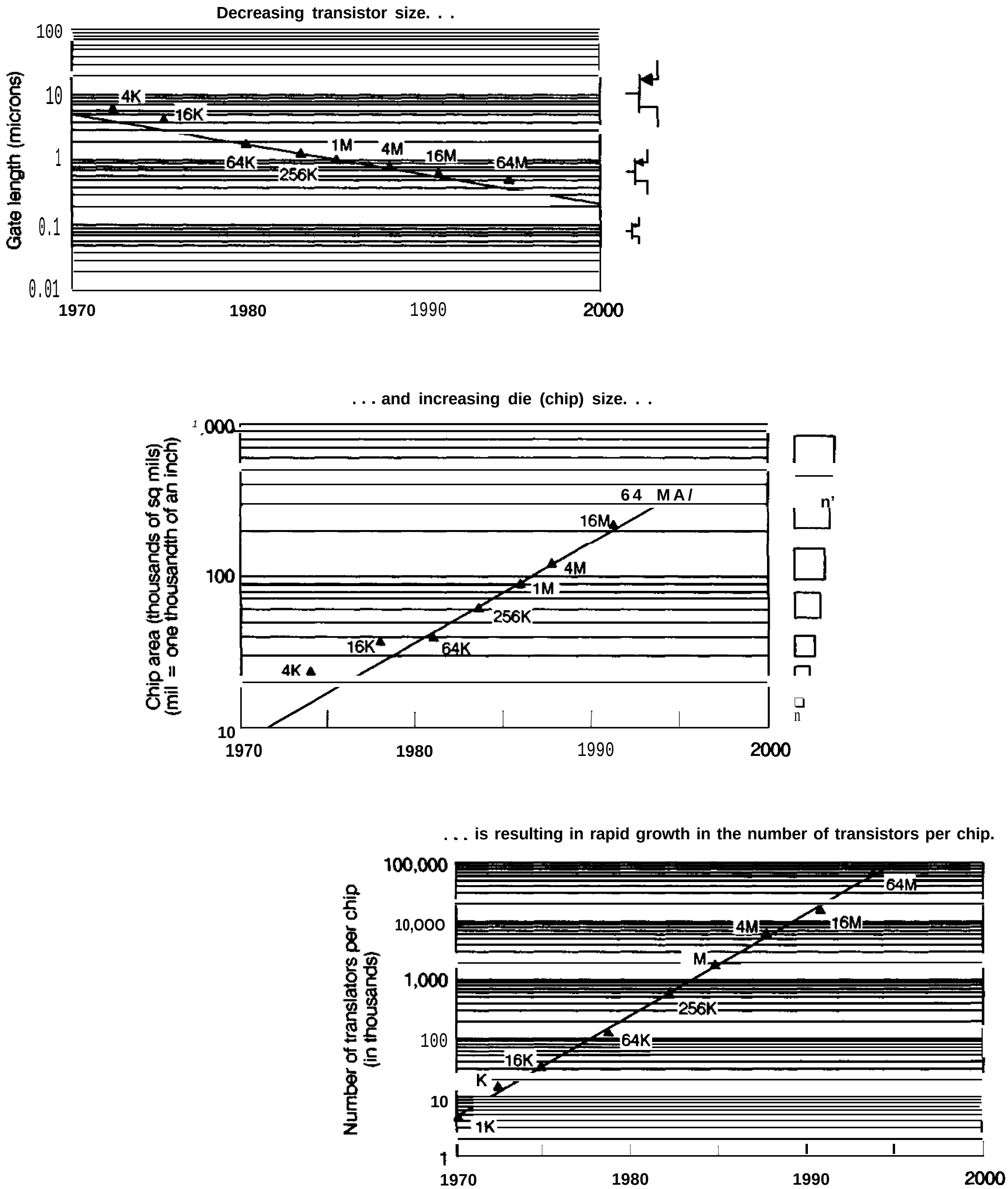
Physical Limits to Transistor Miniaturization

What are the prospects for increasing densities of transistor based integrated circuits beyond 1 gigabit DRAM and 400 million transistor microprocessors? On this question, experts' opinions

[1] DRAM is the primary means of storing information in a computer system temporarily while the computer is working on the information. Mass storage (e.g., hard disk) is used for permanent storage.

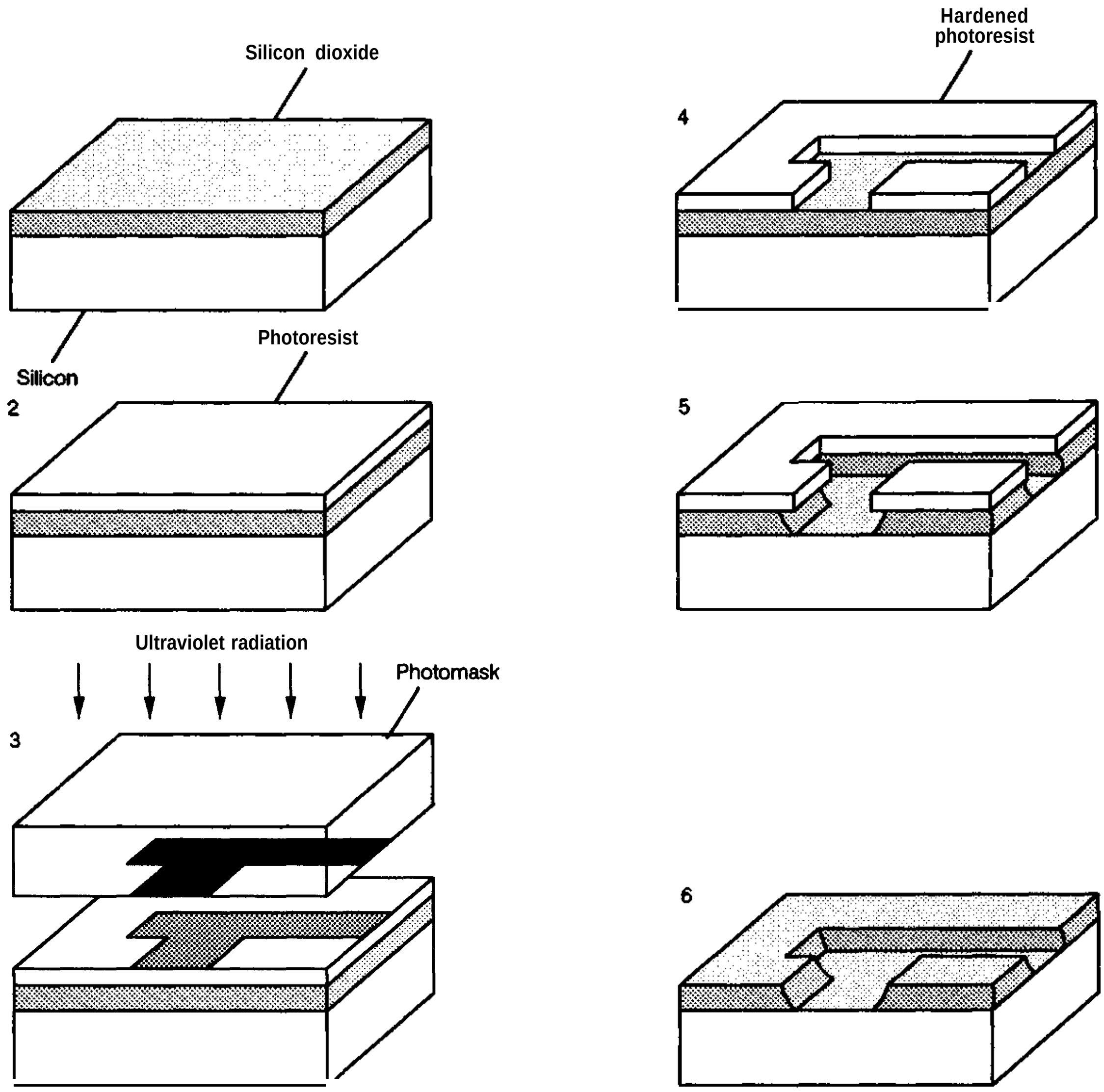
[2] Electron-beam lithography is currently used in production of masks and may be useful in some production applications, e.g., manufacturing chips for high-performance computers.

Figure 2-1 –Transistor Trends



SOURCE: Office of Technology Assessment, 1991. Data from Intel Corp., David Ferry, Arizona State University, and Graydon Larrabee, Texas Instruments.

Figure 2-3-The Photolithographic Process



Photolithography is the process by which a microscopic pattern is transferred from a photomask to a layer of material in a circuit. In this illustration a pattern is shown being etched into a silicon dioxide layer (shaded) on the surface of a silicon wafer. The oxidized wafer (1) is first coated with a layer of a light-sensitive material called photoresist (2) and then exposed to ultraviolet light through the photomask (3). The exposure renders the photoresist insoluble in a developer solution; hence a pattern of the photoresist is left wherever the mask is opaque (4). The wafer is next immersed in a solution of hydrofluoric acid, which selectively attacks the silicon dioxide, leaving the photoresist pattern and the silicon substrate unaffected (5). In the final step the photoresist pattern is removed by means of another chemical treatment (6). There are variations on this process such as use of photoresists that become soluble instead of insoluble (4), and use of reactive gases instead of liquid acid solutions for etching (5).

SOURCE: Adapted from William G. Oldham, "The Fabrication of Microelectronic Circuits," *Microelectronics (San* Francisco, CA: W.H. Freeman & Co., 1977), p. 47. Copyright (c) 1977 Scientific American Inc.–George V. Kelvin.

most common current technology uses visible or ultraviolet wavelengths of light for the photolithographic process.

The current state-of-the-art photolithography uses ultraviolet light, typically with a wavelength of less than 400 nanometers. Use of excimer laser sources could achieve wavelengths less than 200 nanometers. By improving mask technology, optics, and resists, ultraviolet systems may be usable to **0.25-** or 0.2-micron minimum feature size—dimensions that are expected to be needed in the mid-1990s. There are several lithography technologies that can create features smaller than 0.25 or 0.2 microns. The likely candidates for the next generation of lithography tools are x-ray lithographies, optical lithographies using phase shift masks, electron-beam lithographies, and ion-beam lithographies. Combinations of the techniques are also possible. (For a more detailed description of the photolithographic process, see app. A.)

Materials and the principles of surface sciences are fundamental to advancing miniaturization of transistors and electronics. Improvements in semiconductor manufacturing rely on understanding how materials react to processing and fabrication techniques. Physical phenomena underlying the critical fabrication steps are not well understood; knowledge has developed mostly from experience, not derivation from physical laws. Better understanding of the physical laws affecting small-scale structures would accelerate advances in miniaturization.

There are more speculative ideas for future fabrication technologies that would require even more rigorous understanding of surface interactions. Some exploratory work is currently underway to use proximal probes to fabricate integrated circuits. Using a scanning tunneling microscope (STM) or some variation of an STM, scientists are beginning to fashion crude structures from individual atoms and clusters of atoms. Researchers have been able to move or deposit atoms on or below surfaces to "draw" figures, maps, and company logos (see photograph). Even if these techniques do not result in usable manufacturing tools, they will increase our understanding of surface interactions of atoms, leading to better understanding of traditional semiconductor manufacturing. Even more speculative is the prospect of creating molecular-sized robots and machines that could be programmed to manufacture virtually any molecular structure (see box 2-A).

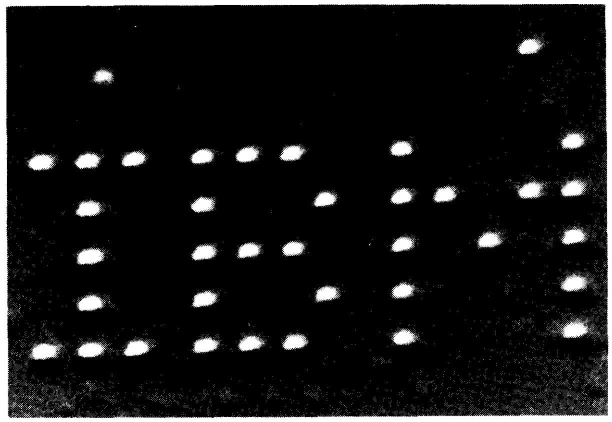


Photo credit: IBM

Scientists at IBM's Almaden Research Center used a scanning tunneling microscope (STM) to move **xenon atoms around on a nickel surface and spell out the company name. The distance between each atom of xenon is about 13 angstroms.**

COMPUTING SYSTEMS TECHNOLOGIES

Computer systems have shrunk dramatically during the last 30 years. Mainframe computers once filled large rooms and required air conditioning to dissipate the heat generated by vacuum tubes and early transistors. Computers have become so small that laptops and notebook computers are more powerful than mainframe computers of 10 years ago. Equivalent power will soon be available in a checkbook-size package. Past miniaturization of electronics has played the major role in bringing this capability about and future miniaturization advances will be driven primarily by electronics (see figure 2-4). Other components in addition to integrated circuits also had to shrink in size to accommodate today's notebook-sized computers. Increased mass memory density, greater circuit board density, and thinner flat panel displays have improved computer system performance and allowed downsizing. Trends toward smallness are expected to continue as customers demand higher quality, higher performance, and portability from smaller boxes.

The technical problems associated with making practical memory or logic systems from molecular devices are substantial and are not likely to be solved in this decade. The most vexing problem is the interface (connection) between the molecule and the circuit itself, a problem common to many forms of miniature transistors. At 0.1 micron, transistors begin to experience problems with high resistance, but a molecular transistor would be smaller still—0.001 microns or less. In order to avoid the electrical interface problem, some researchers are exploring optical interfaces. The diameter of an optical interface, however, is limited by the wavelength of light. The stability of the molecules is also a problem. To be useful for computation, a molecule must remain in a specific configuration until changed by an external signal. Individual molecules sometimes change configurations unexpectedly. Using clusters of molecules makes them easier to connect to circuits and reduces the errors in the stored data, but makes the computing device larger.

Related research is underway in the use of biologically derived or organic material for storing information or computing. These approaches minimize the interface and stability problems of individual molecule computation. A few U.S. companies are working on organic materials for optical disks and at least one Japanese firm, Mitsubishi, is working on an optical disk that will use bacteriorhodopsin as the storage material.[5] Few materials have suitable properties for computing; this has been a major stumbling block for molecular computing. U.S. research is directed at better understanding materials that might serve as the basis of future molecule-based computers. The more immediate results may be faster data storage, but proponents of molecule-based computing hope that the experience gained will lead to true molecule-based computing and processing systems in the future.

Fabrication Technologies

There are several manufacturing technologies that are important in making semiconductor devices. The most critical manufacturing technology by many accounts, is lithography–the techniques used to pattern and etch transistors and their interconnections on a substrate like silicon or GaAs.

There are several different lithographic technologies including photolithography, electron-beam lithography, ion-beam lithography, and x-ray lithography. In addition, there are several novel technologies still in early stages of development—e.g., scanned photolithography, combined patterning and growth, and proximal probe fabrication.

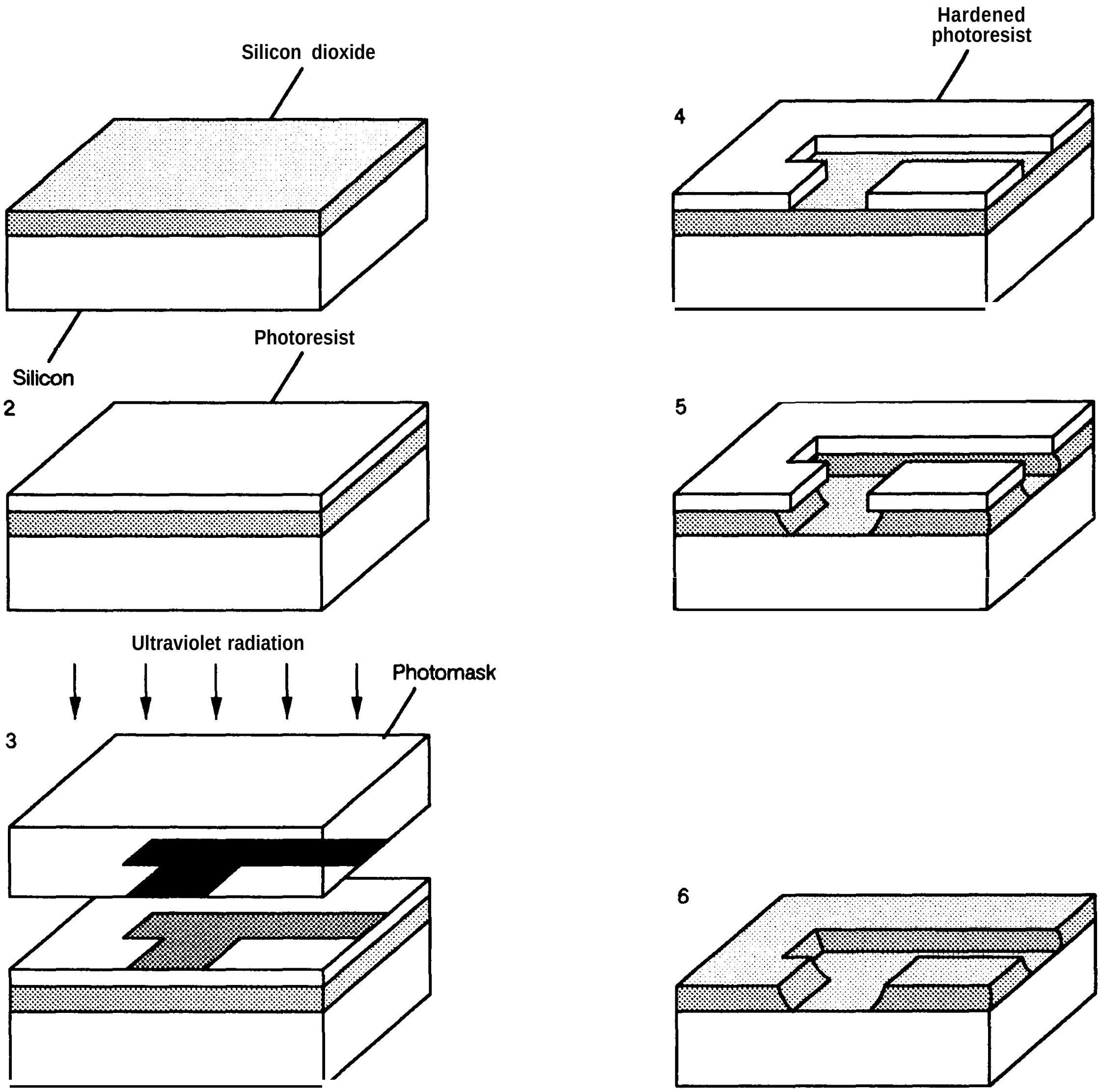
One of the most critical steps in lithography is exposing the resist—usually an organic compound layered on top of the semiconductor wafer–to an energy source (see figure 2-3). The energy source can be optical, ultraviolet, or x-ray. It can also be a beam of charged electrons or a beam of charged atoms (ions). Some of the resist is exposed to the energy source and some is not, depending on whether the resist lies under a transparent or opaque portion of the mask. In the places exposed to the energy source, the resist is modified so that certain chemicals can dissolve it.[6] Exposing the wafer with a series of etching chemicals removes the resist and a layer of material (usually silicon dioxide) underneath. The remaining resist is then removed by another chemical that does not affect the semiconductor material. A layer of material is typically deposited again and the process is repeated—as many as 12 or more times—to make an integrated circuit. The minimum feature size that can be formed is determined primarily by the precision that the energy source can be focused to discriminate between the areas of the resist that are exposed to the energy and those that are not.[7] The

[5] Robert Birge, Syracuse University, personal communication, July 29, 1991.

[6] There are different types of resists. Exposure to radiation causes some types to become susceptible to the subsequent etching step, and causes others to become resistant to etching.

[7] Other key factors are the ability to align subsequent layers of masks to create the proper vertical geometry and the ability to control the rate and direction of etching.

Figure 2-3-The Photolithographic Process



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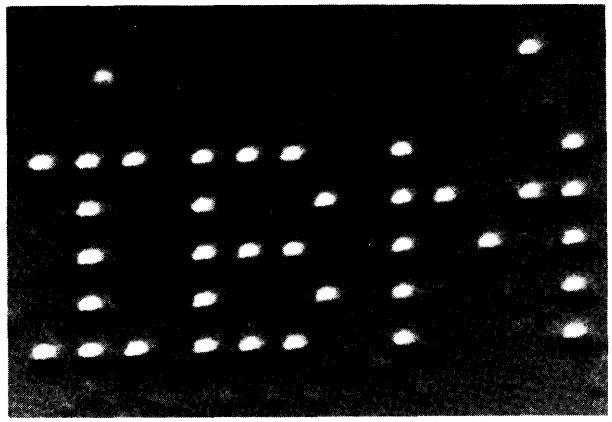

Photo credit: IBM

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Box 2-A—Molecular Machines

With electronics continuing to shrink and advances in the ability to make tiny mechanical devices, one wonders if there is a limit to the ability to manipulate small structures. Some theorists speculate that humans could control individual molecules precisely enough to build molecule-sized machines and robots. These machines would be so small that millions would fit in one of the micromotors described elsewhere in this report. Various terms have been used to describe the concepts;[1] here they will be referred to as "molecular machines."

The process of DNA replication and protein generation demonstrates that molecules can store information and use it to fabricate complex molecular structures. Molecular machine theorists claim humans will be able to create molecular machines to perform similar functions.[2] These molecular robots could be programmed to manufacture virtually any molecule-based structure Possible--everything from hamburgers to spaceships. According to proponents, such technology could control pollutants, create flawless materials, and provide almost limitless computing power. But they warn that there are potentially dangerous applications such as weapons more powerful than nuclear bombs, or machines that replicate uncontrollably, reducing the earth to a "gray goo."

Significant barriers prevent the immediate implementation of molecular machine concepts. The only tools that can directly manipulate molecules are proximal probes, e.g. the scanning tunneling microscope (STM). Proximal probes allow imaging and manipulation of atoms on a surface. Although STM technology is advancing rapidly, manipulating molecules and atoms is awkward and time consuming-a simple molecule has yet to be fabricated.[3] Problems with reliability of molecular-sized systems might make them impractical or delay their development. Because of their extremely small size, molecular machines are especially susceptible to influences such as thermal noise and radiation damage. Molecular machine system designers must compensate for these damaging effects. In many molecular machine application concepts, e.g., random access memory (RAM) or gene sequencing, molecular scale systems must interface with larger scale systems. In addition, molecular machines must interface with the outside world in order to be "programmed." The problems of interfacing molecules to larger scale systems hamper the ability to miniaturize many devices,[4] including many of those proposed by molecular machine designers.

Should Policymakers Be Concerned?

Because of the tremendous impact molecular machine technology might have, there are calls for government to monitor progress in the field and fund research toward its realization.[5] OTA attempted to determine the importance of molecular machine ideas to policymakers by assessing the basis of the molecular machine concepts and prospects for their development.

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[1] Other terms used currently and in the past include "nanotechnology," "Feynman machines," "eutaxic control," "assemblers," and "nanobots." The term "nanotechnology" is particularly confusing because it is also used to refer to sub-micron electronics, micro-sensors, quantum electronics, and micromechanics. As a result, molecular machine concepts are often portrayed in the same light as those other technologies that are very different in size, technology base, and time to realization.

[2] For more detailed descriptions of molecular machine concepts, see K.E. Drexler, *Engines of Creation* (New York, NY: Anchor *Books,* 1986) or references 7 and 8.

[3] Donald Eigler, IBM Almaden Research Center, personal communication, May 1991. Fabrication of a simple molecule a reasonable near-term expectation.

[4] See the descriptions Of transistor miniaturization in this chapter for details.

[5] See Susan G. Hadden et al., *Assessing Molecular* and Atomic Scale *Technologies (MAST)* (Austin, TX: University of Texas at Austin Board of Regents, 1989); and Chris Peterson, "Molecular Manufacturing for Space," *Forsight Update*, No. 12, p. 8.

Continued on next page

Despite the skepticism of many researchers contacted by OTAand the evident controversial nature of their ideas, there has been little written criticism of molecular machine Concepts.[6] The two seminal articles on the topic of molecular machines were written by Richard Feynman[7] and Eric Drexler.[8] The arguments for and against molecular machines tend to be conceptual and not refined to the point of discussing architectures or systems the debate so far seems to center on whether such devices are possible within bounds of natural law. Written criticism tends to focus on more specific suggestions and architectures in the related field of molecule-based electronics rather than molecular machine concepts. The scarcity of criticism maybe due to the reluctance of scientists to denounce new concepts in publications.[9]

There are many concepts of what impossible within the bounds of natural law--e.g., steam-powered computers and interstellar travel-but they do not exist as technologies. While science can determine whether a concept is feasible, technology development is influenced by unpredictable economic and social factors. As a technology, molecular machines are non-existent; the only work to date has been conceptual and computational modeling.

When will molecular machine technology be developed? Estimates from the proponents of the concepts are 10 to 30 years, while others predict from centuries to "never." One of the basic components of a molecular machine technology base would be a protoassembler, a molecular machine capable of fabricating other molecular machines, The earliest prediction for development of protoassemblers is 5 to 10 years.[10]

Is There a Government Role?

To date, no proposal for research on molecular machine development has been received by a Federal agency. Basic scientific and engineering research in the fields of materials science, chemistry, molecular biology, advanced electronics, molecular modeling, and surface science are being funded by many Federal agencies and would be necessary precursors to the realizationof molecular machines. It is impossible to estimate the level of funding, however, since there is no exact definition of precursor technologies. There are a few small research efforts explicitly addressing molecular machines concepts in U.S. academia and industry and Japanese government.[11]

Development of a framework for government regulation and oversight of molecular machine technologies has been suggested by several analysts, driven by fears of abuse or accidents associated with the development of these technologies. The communities of researchers working on these precursor technologies is rather small and the concern over accidents or misuse of the technology is well known among them. Government regulation at this stage would be premature, might hamper emerging research efforts, and have uncertain advantages. The question of regulation and oversight should be revisited and analyzed in greater depth if developments in the field bring the technology closer to reality. The development of the first protoassembler might bean appropriate milestone to reconsider government regulatory involvement.

[6] OTA conducted a literature search of articles that reference the two articles and analyzed them for critical and supporting arguments.

[7] R. Feynman, "There's Plenty of Room at the Bottom," *Miniaturization*, A. Gilbert (cd.) (New York, NY: Reinhold, 1961), pp. 282-2%.

[8] K.E. Drexler, "Molecular Engineer@: An Approach to the Development of General Capabilities for Molecular Manipulation," *Proceedings of the National Academy of Science USA,* vol. 78, No. 9, September 1981, pp. 5275-5278.

[9] Rolf Landauer, "Poor Signal to Noise Ratio in Science," *Dynami"c Patterns in Complex Systems,* J.A.S. Kelso, A.J. Mandell, M.F. Shlesinger (eds.) (Singapore: World Scientific, 1988), pp. 388-394.

[10] Eric Drexler, Foresight Institute, personal communication, March 1991.

[11] In the United States, one researcher is Performing molecular modeling at Xerox Palo Alto Research Center. A nonprofit organization, Institute for Molecular Manufacturing, in Palo Alto, California was formed this year and plans to sponsor research in the future. No projects in Japan or Europe are explicitly directed at molecular machine development, although the Hotani Molecular Dynamics project sponsored under the Japanese Exploratory Research for Advanced Technology (ERATO) program addressed molecular machine concepts in addition to its regular line of scientific investigation.

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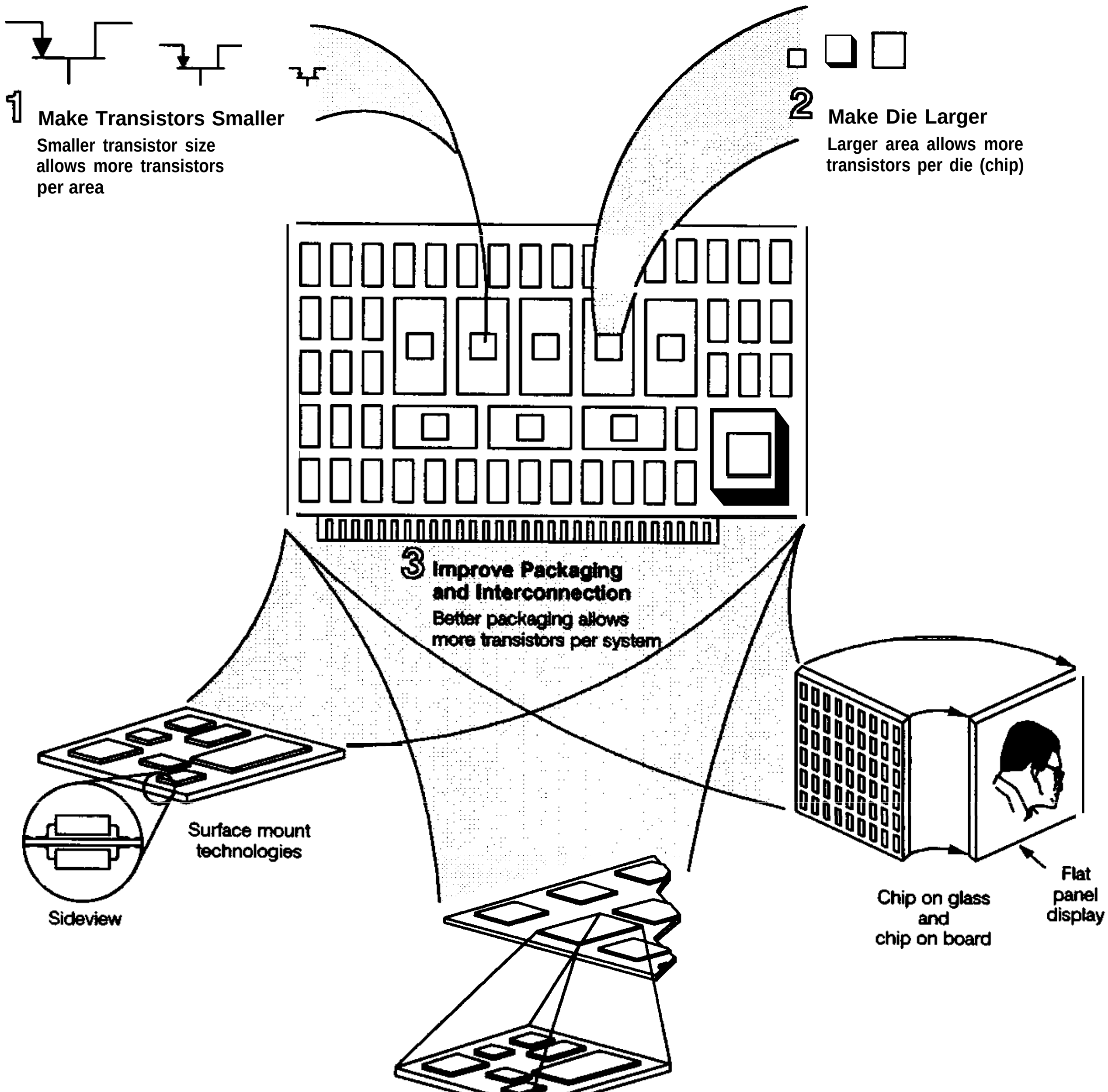
Figure 24–Three Approaches to Electronics Miniaturization



Three basic strategies are used to miniaturize electronics systems. By making each transistor smaller (l), more can be placed on an integrated circuit, incorporating the functions of other chips. Increasing the size of the chip (2) has a similar effect by increasing the available area for transistors and their interconnections. These first two approaches have been the driving force behind electronics miniaturization for at least the past two decades. Improved packaging (3) is a way to improve use of space on a printed circuit board. Atypical printed circuit board has only a small fraction of its space covered with integrated circuits; the rest is primarily packaging and interconnection.

SOURCE: Office of Technology Assessment, 1991.

Display Technology

The size of a typical cathode ray tube (CRT) desktop computer display is about a cubic foot. New technologies, e.g., as liquid crystal display (LCD) and electroluminescence displays, have allowed the development of flat panel displays that occupy a tenth of the volume. Flat panel display technologies are discussed in detail in the OTA report The ***Big Picture:*** *HDTV & High Resolution Systems. New* technologies required to advance high-resolution video technology are many of the same that are required for advanced electronics and more powerful computer systems.[8] Japanese producers of flat panel displays favor LCD technology and are increasingly adapting it to larger screens, but current fabrication techniques are limiting screen size to about 15 inches. Further increases in screen size await improved lithography.

Data Storage

"Mass Storage" refers to storage technologies with large capacities, including optical and magnetic media that retain data when the power is off. These devices encode data on a surface that can change its magnetic or optical characteristics. By moving the surface under a device that can sense and change the characteristics of the surface—a read/write head—data is stored and retrieved.

Semiconductor memory storage increases capacity as constraints on transistor miniaturization can be overcome, but mass storage operates on different physical principles and therefore has different limitations. There are two major types of mass storage technologies—magnetic and optical. The trends in magnetic storage show no sign of slowing as they approach densities that will put 1 billion bits onto 1 square inch. Researchers at IBM's Almaden Research Center have demonstrated such densities.[9] Today's storage densities are about 50 to 100 million bits per square inch in high-end storage systems. Optical storage technology uses lasers to write and read data from an optical disk and is limited by the size of the laser beam spot on the disk. The spot size, in turn, is limited by the wavelength of the laser source. Most optical disks today use a red (wavelength of 800 nanometers) laser to write and read data. Efforts are underway now to develop blue lasers (wavelength of 400 to 500 nanometers) that would have smaller spot sizes and be able to increase the capacity of optical disks by four times.

Another technique that promises much higher densities uses STM[10] to write and read data. The STM and related instruments use sharp tips in close proximity to a surface to create an atom-by-atom image of the surface. These tools also have the capability to physically modify surfaces by either etching away or building up a few hundred atoms at a time. Such techniques could result in massive data density-more than 1,000 billion bits (1 terabit) per square centimeter. The major problem with STM and related approaches to data storage is that the data access speed is painfully slow.[11] There is research currently underway at a few labs to combine many tips in parallel, increasing the speed of writing and reading. These approaches remain speculative, but might yield useful technology in the long term.

Interconnection and Packaging

The basic packaging component of most computer systems is one or more circuit boards. Various components are placed on the circuit board and interconnected with strips of metal. Due to manufacturing costs, the number of components

[8] The techniques used to make LCD displays are many of the same that are used to make integrated Circuits. For more information see OTA's Background Paper, *The Big Picture: HDTV & High-Resolution Systems,* OTA-BP-CIT-64 (Washington, DC: U.S. Government Printing Office, June 1990).

[9] Robert M. White, "Peripherals," *IEEE Spectrum,* February 1990, pp. 28-30.

[10] See app. A for details on the STM.

[11] One estimate is that 32 centuries would be required to write one square centimeter with one proximal probe. See James S. Murday and Richard J. Colton, "Proximal Probes: Techniques for Measuring at the Nanometer Scale," in *Chemistry and Physics of Solid Surfaces,* R. Vanelow and R. Howe (eds.) (New York, NY: Spnnger-Verlang, 1990), p. 347.

is the greatest contributor to the overall cost of an electronics system (see figure 2-5). System designers seek to reduce the number of components on a board to improve reliability as well. The interconnecting strips of metal on a board and connections between boards are more likely to break than connections elsewhere in the system. Ever since the invention of the integrated circuit, the best way to reduce costs and increase reliability is by putting more transistors on integrated circuits, hence reducing the number of circuit board components. By decreasing the size of each transistor and their interconnections, more transistors have been crammed onto integrated circuits.

While the density of circuits on a chip have been increasing, the size of the chip has been increasing as well. The first microprocessor in 1971 was on a 19,000 square mil (1 mil = one-thousandth of an inch) chip. For the next 20 years, chip size increased by about 14 percent per year. Current microprocessors are on chips of about 260,000 square roils. Chip size may rise even faster over the next few years, yielding a chip size of 625,000 square roils in production by 1994.[12] Since the probability that a chip is defective increases with its size, chip size is limited by the number of defects on a wafer (see figure 2-6).

If the increase in chip size is taken to its limit, an entire wafer can become one large circuit. Since a typical wafer produces about a hundred chips, a huge number of transistors could be put on one wafer. But there are significant problems with such an approach. There are defects in every wafer (primarily caused by particulate from the manufacturing equipment), so a wafer-scale circuit is virtually guaranteed to have defects. With the high defect rate, strategies for routing connections around defective components must be considered in circuit design. Another problem is that the complexity of interconnecting wafer-scale circuits increases the number of processing steps. Finally, the fine lines of metal used to link the imbedded transistors together are not suited for the relatively long interconnections needed for wafer-scale integrated systems. There are some specialized applications that could use wafer-scale integration such as image processing and large memory storage,[13] but unless fabrication problems are solved, it will likely not be an important technology. Applications that have regular designs —e.g., memory is essentially the same circuit pattern repeated over and over—have achieved marginal success with wafer-scale integration because errors in the circuit are relatively easy to detect and correct or bypass.

Hybrid wafer-scale integration—known as multichip module (MCM)—is another approach to increasing circuit density. MCMs take several chips, place them on a substrate (usually silicon or a ceramic), and connect them with thin films of conducting metal using techniques like those used in integrated circuits. Multichip modules place chips closer together than is possible using single chip packages—an important advantage as chip speeds increase. The distance a signal can travel in one clock cycle—the "heartbeat" of a computer system—shrinks as cycle times shorten. Machines with clock cycles of 2 nanoseconds will soon be available,[14] which corresponds to 500 megahertz. (The fastest of today's personal computers operate at about 33 to 50 megahertz.) Reliability is also enhanced because the number of printed circuit board connections and board-to-board connections are reduced.

MCMs have been successfully used in the IBM 3090 and the NEC SX-AP; high manufacturing costs, however, keep them from being used in mass production items like personal computers and workstations.[15] The Microelectronics & Computer Technology Corp. (MCC)—a private consortium of electronics companies—has developed a MCM technology capable of producing

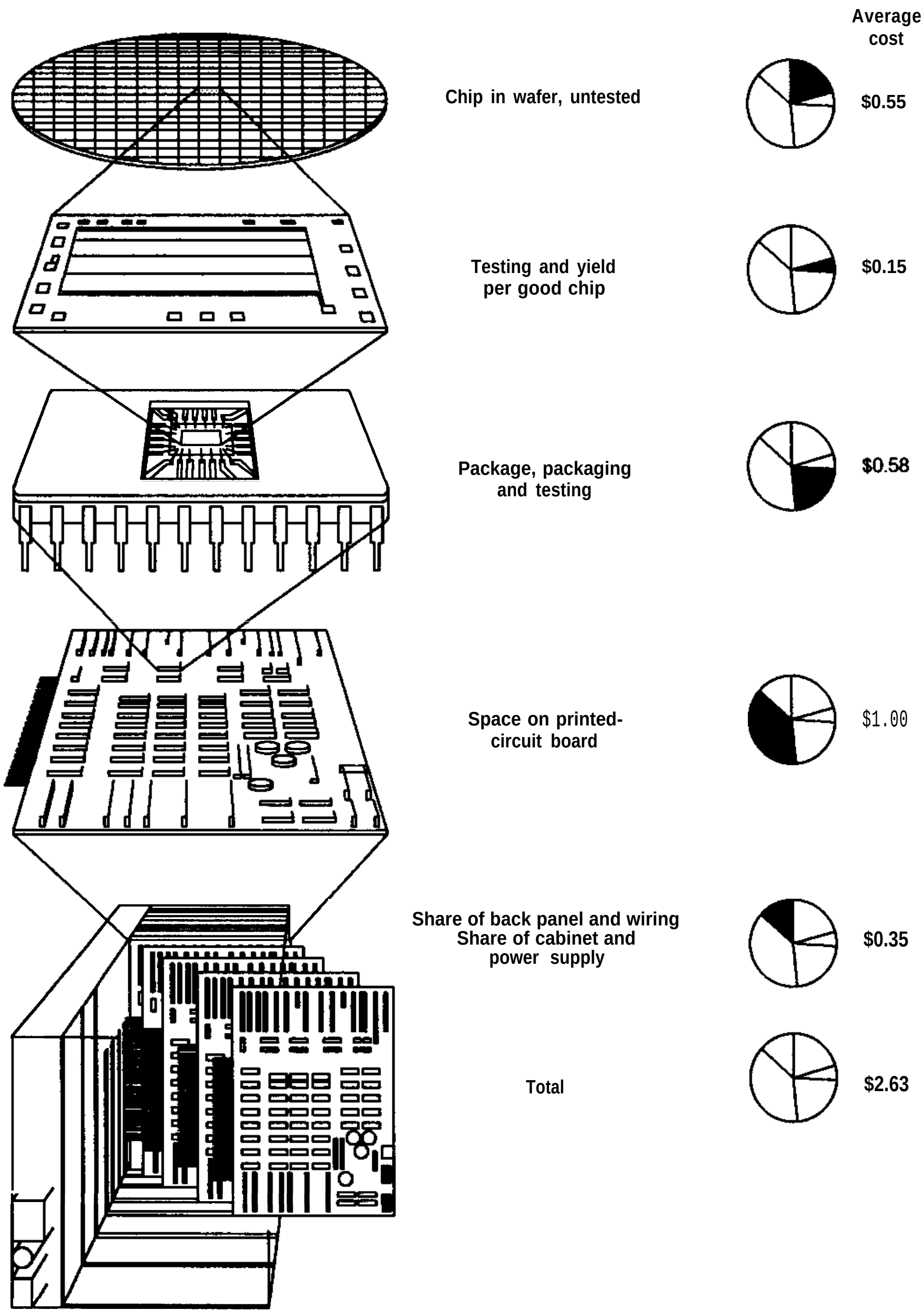
[12] Jerry Sullivan, "The Next Generation of Electronics Design Automation Technology for Systems in Silicon," MCC Technical Report No. CAD-043-90, Jan. 24, 1990.

[13] "A Dream Remembered," *The Economist, Nov. 17, 1990,* p. 12.

[14] Dennis Herrell and Hassan Hashemi, "Hybrid Wafer Scale Integration," MCC Technical Report P/I-329-89, 1989.

[15] Ibid.

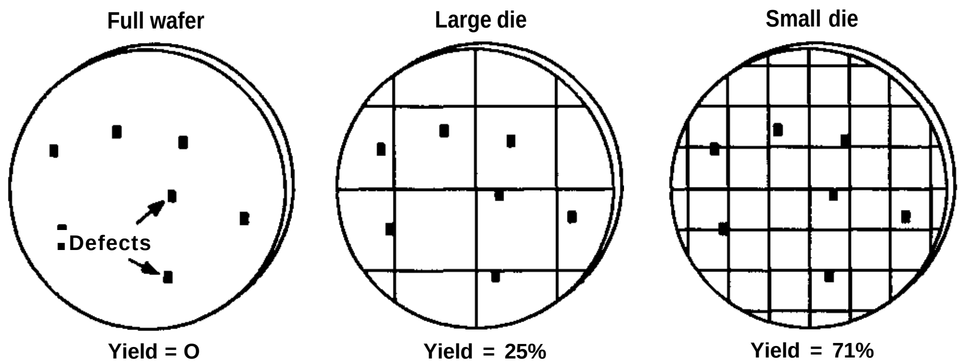
Figure 2-5–Relative Cost of a Chip at Different Levels of Interconnection



Space on the printed circuit board is one of the most expensive commodities in a system design. By integrating more functions onto a chip, system designers can reduce the number of chips on board, lowering overall system cost. The illustration shows the steps that a chip goes through on its way to becoming part of a computer system and the relative cost per chip for each stage.

SOURCE: Adapted from Ivan E. Sutherland and Carver A. Mead, "Microelectronics and Computer Science," ***Microelectronics (San*** **Francisco, CA: W.H. Freeman &Co., 1977), p. 113. Copyright(c) 1977 by Scientific American, Inc. All rights reserved. Data from Graydon Larrabee, Texas Instruments, personal communications, Sept. 20, 1991.**

Figure 2-6- Relationship of Die Size and Yield



Smaller die (chip) size means higher yield (percentage of good chips) for a given density of defects.

SOURCE: Adapted from Sand, *Silicon, Systems,* Howard K. Dicken (cd.) (Scottsdale, AZ: DM Data Inc., 1986), p. 7-12.

computers that are fast (3 nanosecond cycle time, or 333 megahertz), use 10 million gates, and cost $5,000. Costs must be reduced further for the technology to be affordable for workstations and personal computers.

A major obstacle to widespread use of MCMs is the lack of standardized interfaces for the hardware and software needed to design the modules. For the last 30 years the electronics industry has been building an infrastructure that is focused on the same objective: improving the performance of the integrated circuit. All the manufacturing equipment and computer software is geared for designing and optimizing a single chip. It is difficult to obtain "naked" chips (dice) outside their package from semiconductor vendors. Computer-aided design and testing are all difficult with MCMs.

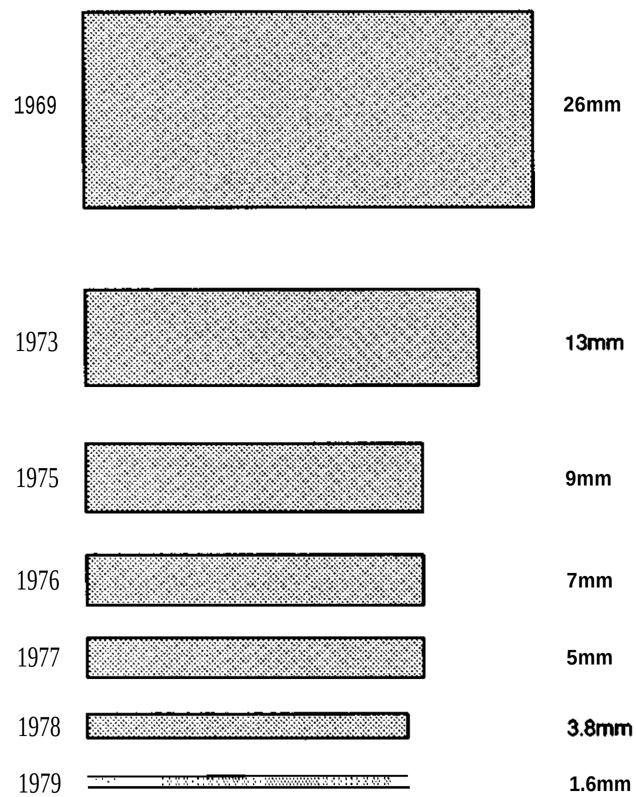
Dissipating the heat generated by dense circuitry is a major problem facing circuit designers. This becomes more difficult as the number of transistors in a chip increases. The simplest approach to accomplish this in a computer system is to flow air over the circuits. In high-performance systems (supercomputers and some mainframes), however, where speed is critical, other means for cooling are often used. Some supercomputers flow inert fluids, e.g., freon, directly over the circuitry. Sometimes fluid distribution systems attached directly to the chip package are used to dissipate heat, a scheme used in several mainframe computers.

Many options for increasing the density of electronic circuits now being investigated operate best at very low temperatures and require external refrigeration units. Advancements in refrigeration and heat dissipation technology are important to pushing the miniaturization of electronics devices. This is because as the cross-section of a conductor decreases, the resistance to current flow rises. Greater resistance means greater heat generation because the same current flowing through a high resistance material creates more heat than in a low resistance material.

The need for better interconnection is greatest in two areas: 1) consumer electronics and 2) high-performance computers. Consumer electronics must combine low costs with high dependability. High-performance computers demand ultra-fast computing speeds and extensive interconnection; while the field is highly competitive, cost is less a factor than performance. In high-performance computing, the need for better interconnection results from the short distance that an electronic signal can travel before another clock cycle starts. Supercomputers push clock cycles to the limit, so designers must devise ways to minimize interconnection distance. The Cray supercomputers have an unconventional circular shape in order to keep components close together and reduce the time needed to communicate among components. Massively parallel computers face an even more serious interconnection problem because many more components (processors) must be connected. A conventional serial (von Neumann architecture) mainframe has only one central processing unit (CPU) that is centrally located so that other components can be closely connected to the CPU. A massively parallel computer may have over 1,000 CPUs that must be interconnected.

In consumer electronics, a major objective is to make the product smaller, lighter, cheaper, and more reliable. Each of these objectives demand better interconnection and packaging. Japanese industry, with its emphasis on consumer electronics, tends to adopt packaging innovations to meet the demands of the market. The impact can be seen in the many consumer products around us (see figure 2-7).

Figure 2-7–impact of Surface Mount Technologies on Calculator Thickness



Implementing surface mount technologies in calculators had a dramatic impact on thickness. Surface mount technologies include surface mounted packages as well as surface mounted keyboards and displays.

SOURCE: VLSI Research.

SENSORS

Sensors are devices that can monitor and translate observed conditions—light level, acceleration, pressure, or temperature—into a signal. The signal can then be transmitted, processed through a system or stored as data. A mercury thermometer, for example, responds to an environmental condition—temperature—and translates to a visual readout indicated by the level of mercury gauged against a calibrated scale. An electrical temperature sensor might sense the change in temperature by measuring the change in voltage across a material. The resulting electrical signal can be manipulated and displayed for read-out.

There are a wide variety of sensors; each can be classified as imaging or non-imaging.[16] Imaging sensors take many measurements of radiated energy from the imaged target. Camcorders, for example, use a charge coupled device (CCD) as an imaging sensor to convert a visible light image to an electrical signal that can be recorded on a VCR tape. Non-imaging sensors act at a single point, typically in contact with the object being sensed. Sensors can be made to sense different substances and energies: electromagnetic radiation, temperature, pressure, acceleration, chemicals, and biological materials. Of the many sensor technologies, a few are key to miniaturizing systems: CCDs, chemical and biological sensors, and micromechanical sensors.

Charge Coupled Devices

CCDs are solid-state image sensors that detect light. They are used in cameras—from camcorders to professional cameras to astronomical cam-

[16] Exceptions t. this classification include some tactile sensors that detect sensations of touch with an array of discrete sensors.

eras on satellites. The resolution of a CCD is determined by the number of picture elements (pixels) on a CCD. The devices are a special kind of integrated circuit with problems similar to other integrated circuit manufacturing. Reducing the size of each pixel improves the pixel density and the image resolution. Increasing the size of the CCD can increase the number of pixels, but defects in the circuit cause yield to plummet as the CCD size increases. Manufacture of CCDs is dominated by Japanese industry. More than 20 Japanese companies manufacture CCD chips and they are the leaders in small pixel size, and innovative design.[17] In the United States, Tektronix, Texas Instruments, and Kodak produce CCDs designed for military, industrial and space applications. The majority of the image-sensing market is in consumer electronics.[18]

Imaging sensors are particularly important to the Department of Defense (DOD). DOD relies on imaging data for things like aiming missiles, detecting rocket launches, and enhancing night-vision. Most DOD applications sense areas of the electromagnetic spectrum that are unique to military needs.

Chemical and Biological Sensors

By combining information technologies with biotechnologies, researchers are developing new sensors that are cheaper, faster, more versatile, and more efficient than previous generations. These sensors, known as biosensors, can detect gases, chemicals, and biological molecules. The first biosensor was invented in 1%2 by Leland C. Clark Jr., but it was not until the 1970s that biosensors came into practical use. The early biological and chemical sensors were relatively large; Clark's first glucose sensor was about a centimeter in diameter.[19] There are many ways to make biological and chemical sensors; some can be made using techniques borrowed from integrated circuit manufacturing. By applying this technology, it is now possible to make sensors that are only a few thousandths of a centimeter wide.

Smaller biosensors have two advantages: 1) they can be placed in areas that were previously inaccessible, and 2) they are fast since the measurement can be done in the field instead of at a central lab. Because they offer similar economies of production as microelectronics, biosensors will become cheap and widely available. Biosensors will be useful in portable systems. A market analysis by Arthur D. Little, Inc. in 1991 predicted that portable biosensors sales would reach $1 billion by 2000.[20] With sensors for substances like glucose, urea, and carbon monoxide available in an inexpensive and small package, portable diagnostic kits could be made available (see box 2-B). The industrial food processing industry is expected to make use of portable biological sensors to determine the freshness of food. Because biosensors are small enough to be placed on the tip of a hypodermic needle, blood chemistry could be monitored continuously by placing several biosensors onto a chip inserted on a catheter tip into the patient during surgery. The capability to measure chemicals concentrations will be useful for process industries such as biotechnology and chemical production.

Miniaturization of biosensors and chemical sensors relies on a device called a chemical field effect transistor (ChemFET).[21] ChemFETs are similar to the field effect transistors (FET) that are used in normal microelectronics. A microelectronics FET conducts electricity (turns on) when a voltage is applied to one of it inputs (gate), creating an electric field in the FET. A ChemFET

[17] U.S. Department of Commerce, "JTECH (Japanese Technology Evaluation Program) Panel Report on Advanced Sensors in Japan," January 1989, p. 40.

[18] Ibid., p. 44.

[19] Jerome S. Schultz, "Biosensors," *Scientific American*, August 1991, pp. 64-69.

[20] "Strong Growth for Biosensors," *New Technology Week*, Feb. 19, 1991, p. 8.

[21] Also known as ion sensitive field effect transistor (ISFET). "CHEMFET" is usually used to refer to sensors that use whole molecules, while "lSFET" refers to sensors designed with ions (charged atoms or molecules).

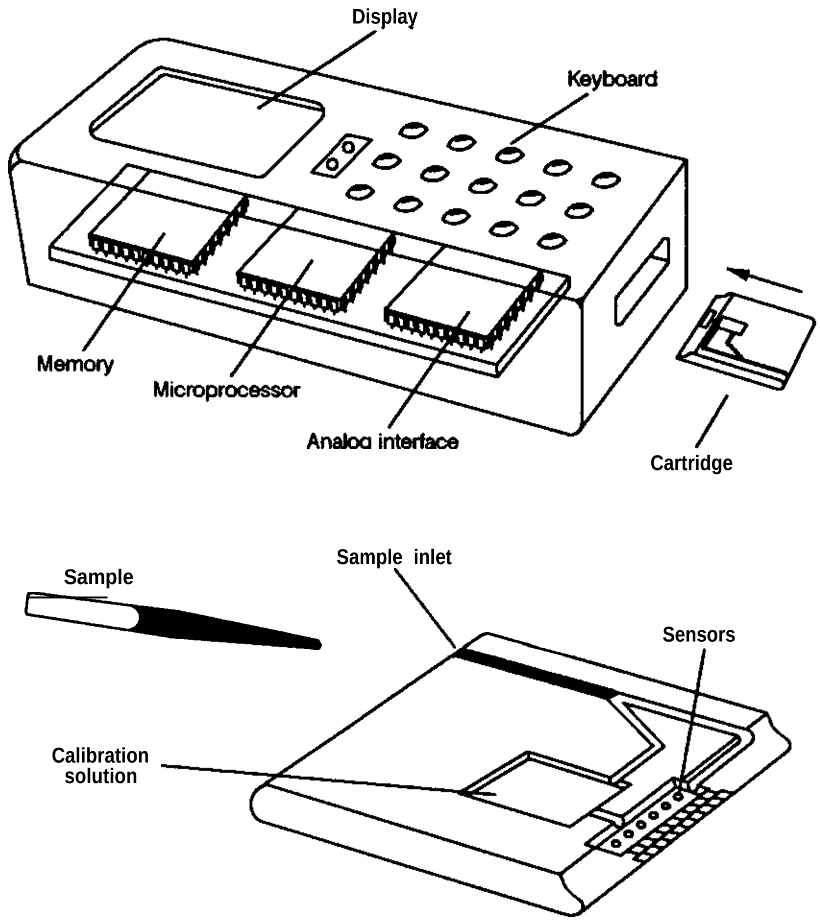
Box 2-B--Bedside Analysis[1]

A hand-held analyzer currently under evaluation at the Hospital of the University of Pennsylvania demonstrates how biosensors might find their way into clinical use. It simultaneously makes six commonly requested chemical measurements on a patient's blood-sodium, potassium, chloride, urea nitrogen, glucose, and hematocrit-producing results in less than 2 minutes. The bedside tests cost more than ones performed in a central laboratory, but their immediacy may make them more effective.

The device achieves accuracy comparable to that of laboratory equipment by using a disposable cartridge containing six biosensors and a calibration sample. A medical worker places 60 microliters of blood in the cartridge; the analyzer then measures both the calibration sample and the patient sample. It displays test results and also stores them, keyed to time and the patient's identification number, for later analysis: The cartridge-based design adopted by manufacturers will make it possible to perform a different set of tests once the appropriate sensors have been developed.

[1]Adapted from Jerome Schultz, "Biosensors, *Scientific American*, August 1991, pp. 64-69.

Figure 2-B-1 -Bedside Analysis



SOURCE: Adapted from Jerome S. Schultz, "Biosensors." *Scientific American*, August 1991, pp. 64-69. Copyright (c) 1977 Scientific American, Inc. All rights reserved.

uses a FET that is specially coated with a chemical or molecules that will create an electric field when the sensor is exposed to a specific chemical, gas, or molecule.

Fiber-optics technology aids biosensor and chemical sensor development and miniaturization. Certain chemical and biological molecules will change their optical properties (either give off or absorb light differently) when exposed to other chemicals or molecules. For example, the enzymes dehydrogenase and luciferase react with testosterone, the male hormone, to produce a secondary chemical that gives off light (fluoresces). A fiber-optic-based glucose sensor might one day serve as the basis of an implantable artificial pancreas.[22] In the meantime, glucose sensors are being incorporated into the latest generation blood sugar monitors for diabetics. These devices are portable, take measurements in seconds compared to hours with earlier monitors, and some function without drawing blood by measuring absorption of light through skin.[23]

[22]Schultz, op. cit., footnote 18.

[23]J. Travis, "Helping Diabetics Shed Pins and Needles," *Science News*, vol. 140, No. 1, July 6, 1991, p. 4.

New generations of biosensors and chemical sensors will take advantage of theircommon heritage within formation technology to integrate logic functions into the same package with biosensors. Integrating logic with sensors can result in more useful devices. For example, a glucose sensor with integrated logic might respond differently to blood sugar levels at different times of day. Integrated circuit fabrication holds promise for high integration by placing biosensors and electronics on the same chip. It also promises reduction in prices because large numbers of sensors can be fabricated at one time. Major challenges remain, however, such as isolating the microelectronics from the environment while allowing the sensor access to the environment.

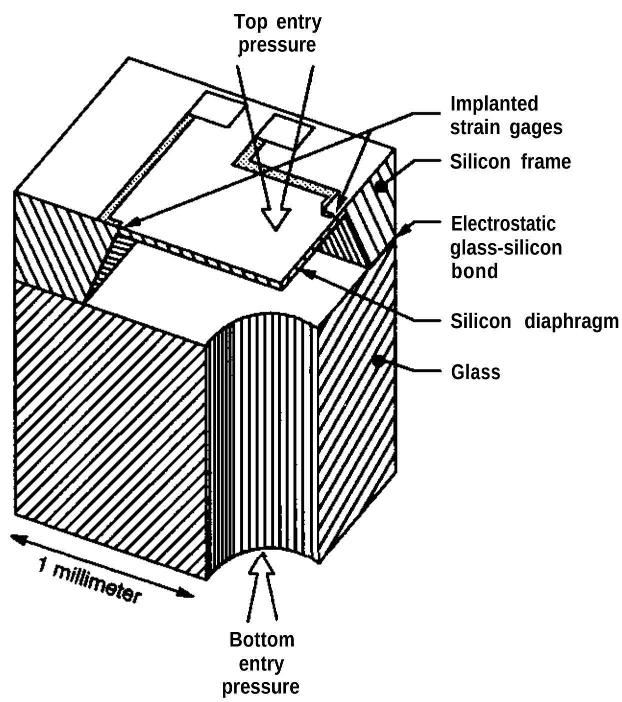
Researchers are actively pursuing refinements to the fabrication processes that will make widespread use of biosensors possible. The yield and uniformity of the manufacturing process needs to be improved before large scale production is practical. Shelf life is a problem with biosensors; compared to microelectronics and fiber optics, biosensors are perishable. Biomolecules that must be affixed to a chip or optical fiber are not stable outside their cellular environments. As a result, biosensors can only be stored for weeks or months—sometimes years. This limitation prohibits some applications, but for some industries short lifetime products are normal and expected. In medicine, for example, instruments are often discarded after use to avoid risk of contamination. The price and capabilities of biosensors in other applications (e.g., detecting explosive gases or critical chemicals in a process) are valuable enough that users are willing to accommodate limited lifetimes.

Micromachined Silicon Sensors

A significant field for future sensor developments will be mechanical sensors—devices that rely on the mechanical properties of a material to sense energy of their surroundings. Since 1958, silicon has been used in pressure sensors. By fabricating a covered cavity, changes in ambient conditions can be detected by monitoring the resistance across resistors on a membrane covering the cavity (figure *2-8)*. Improvements in silicon processing technology have reduced the size and cost of silicon pressure sensors, with major gains made during the 1980s. Cost has gone from about $1,000 per sensor in the 1960s to a few dollars per sensor today. The 1958 silicon pressure sensor that was half an inch wide is now one hundredth of an inch wide. Growth in the 1980s was very strong; silicon pressure sensors are 60 percent of the pressure sensor market—up from 40 percent in 1985 and 16 percent in 1980.[24]

Silicon mechanical sensors are also used to detect acceleration. Accelerometers are made with a mechanical silicon structure that places a mass of material—the "proof mass''—on the end of a thin "arm" of silicon. Acceleration makes the

Figure 2-8-Cut-away View of a Silicon Pressure Sensor



SOURCE: Adapted from Janusz Brysek et al., *Silicon Sensors and Microstructure* (Fremont, CA: NovaSensor), 1990, p. 7.3.

[24] Janusz Brysek et al., *Silicon Sensors and Microstructures* (Fremont, CA: NovaSensor, June 1990), p. 2.18.

silicon arm bend; the degree of bending determines the acceleration. Accelerometers are finding applications in automobiles for airbag deployment and automatic suspension systems. Analog Devices, Inc., for example, is using a surface-micromachined cantilever as the basis for a accelerometer. The separation between the cantilever and the chip surface changes with acceleration, changing the voltage. The voltage change can be translated into an acceleration measurement.

The miniaturization of silicon sensors resulted from developments in micromachining–a technique to precisely shape the surface of a material such as silicon. Silicon in its crystalline form has different orientations in the crystal that can be specified for a particular silicon wafer. Chemicals used to etch silicon "eat away" crystalline silicon at different rates depending on orientation of the crystal to the surface. This process is called preferential etching. By combining preferential etching with special chemicals that stop short the etching process, complex structures can be created in silicon. This technique is known as "bulk micromachining," and has been used since the 1960s.

Use of "sacrificial layers''—technique developed during the 1980s--can create more intricate structures. Sacrificial layers are thin films (usually less than 10 microns) that are removed by etching chemicals to release movable parts from the substrate (see box 2-C). The process of using multiple layers of sacrificial layers to create complex structures is called surface micromachining. Using surface micromachining, researchers at the University of California at Berkeley and at AT&T Bell Labs fabricated a working motor about the width of a hair (100 microns) in 1988 (see photograph). That achievement set off a flurry of research activities. Laboratories around the world were soon duplicating and improving upon the original work. Work at the Massachusetts Institute of Technology (MIT) improved the sacrificial layer technique, making it more compatible with traditional silicon electronics processing. The Karlsruhe Nuclear Research Center in Germany developed a variation on the surface-micromachining technique known as "LIGA." It uses x-ray lithography technologies to fabricate microcomponents from other materials including plastic and metal.

The new complex structures have created a need for better understanding and characterization of the materials used in the structures. Silicon is a well known material, but not enough is understood of its mechanical properties. Structures that are released from the substrate, for example, can warp due to strains in the material. In microelectronics these strains are not important because structures remain connected to the substrate, but for surface micromachining, these strains can ruin a component. Wear and friction are not well understood at such small scales, and researchers need to understand these properties to improve the reliability of micromotors and other movable parts. Characteristics of surface interactions, flow of fluids, and air flow are not well understood at such small scales. Under-

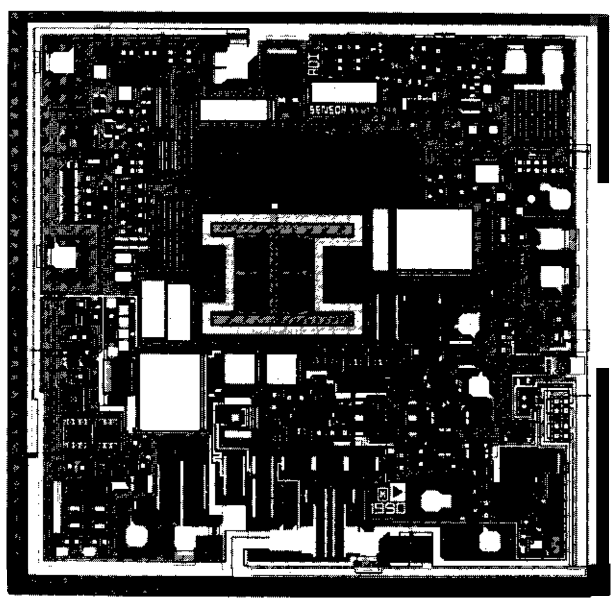


Photo credit: Analog Devices, Inc.

An acceleration sensor (accelerometer) made by Analog Devices, Inc. will be the first commercial product that uses surface micromachining, a new processing technique that uses sacrificial material layers to free structures from a substrate. The microstructure, similar to ones fabricated at the Berkeley Sensor and Actuator Center, can be seen in the center of this microphotograph of the sensor chip. The sensor is surrounded by electronics that provide calibration and signal conditioning.

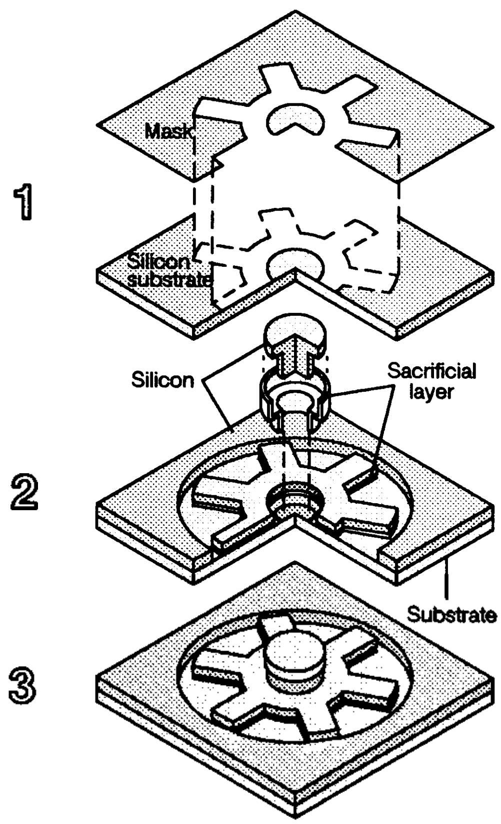
Box 2-C--A New Way To Machine

1. The pattern of the gear is transferred to the substrate by shining ultra-violet or x-ray light through a stencil-like mask.

2. This sequence is repeated several times to achieve a structure that has alternating layers of silicon and "sacrificial layers." (See the description of fabrication technologies in this chapter and app. **A** for details.)

3. The sacrificial layers can be dissolved in a chemical that doesn't disturb the silicon. After the sacrificial layer is removed, the gear is free to rotate. A restraining hub prevents it from flying off the surface of the chip.

Figure 2-C-1 -Surface Micromachining



SOURCE: Sharon Begley "Welcome to Lilliput," Newsweek, vol. 117, No. 5, Apr. 15, 1991, pp. 60-61. Artist Jared Schneidman.

standing fluid flow at such small scales will be important if the technology is used for chemical and biological processing applications.

Future progress in micromachined sensors are in three areas of improvement:

1. design and fabrication processes will improve performance and expand applicability;
2. manufacturing technology will become more important as sensors become commodities; and
3. packaging of the sensor is the third challenge, since reduction in packaging costs has a significant impact on cost of the final product.

Manufacturing technologies and procedures have received insufficient attention in the past.[25] This could hold particular peril for U.S. industry if it is not remedied as it competes with Japanese companies attuned to the value of robust manufacturing methods.

ACTUATORS

Actuators translate a signal to motion or force. A solenoid valve is a common type of actuator that relies on electromagnetic forces to move a plunger arm to open and close a valve. Electrostatic actuators are promising small-scale actuators because electrostatic fields can easily be created in micro-structures and are relatively powerful at small scales. Recent developments indicate electromagnetic actuators are promising as well. Small actuators have also been made from piezo-electric material[26] and shape memory alloys.[27]

Micro-Electro-Mechanical Actuators

Surface micromachining techniques are used to fabricate micro-structures with moving parts.

[25] Ibid., p. 2.18.

[26] Piezo-electric materials contract or expand when a voltage is applied.

[27] Shape memory alloy materials change shape with a change in temperature.

Researchers at the University of California at Berkeley and AT&T Bell Labs fabricated motors in 1988 using these new techniques. These motors are typically about 100 microns in diameter (the width of a hair) and about 3 microns deep. Minuscule motors have also been fabricated at University of Utah and AT&T Bell Labs using more traditional machining techniques that are as small as 500 microns in diameter. These motors produce more power than the smaller motors produced by surface micromachining and might be useful in applications such as microsurgery or drug delivery.[29] Small actuators could also be used in consumer items, (e.g., cameras, cassette players, video recorders, and toys) robotics and defense applications.

Tiny levers, gears, and other mechanical assemblies can be etched from silicon with the same surface micromachining techniques used to make motors. Gears, levers, and the like might be useful for transmitting motion and force. At such small scales, these mechanisms might be useful forma-nipulating light, low-mass objects. There are many potential applications in optics; several materials that can transmit, emit, or reflect light can also be used in the construction of microactuators. Tiny mirrors on movable levers or gears could serve as optical switches or light modulators by moving from one position to another. Moving chemicals, fluids, and cells is currently the object of much research. Electric fields and ultrasonic waves are demonstrated techniques that are being refined through research and development at university and industrial laboratories. Hewlett-Packard and Canon use bulk-micromachined devices to dispense ink for their thermal ink jet printers.[30]

Integrating Actuator, Sensors, and Electronics

One of the most exciting aspects of making tiny structures in silicon and other materials is the prospect of combining sensors, actuators, and electronics into integrated systems on a single chip. The greatest prospect for near term applications is probably science and engineering instrumentation.

Chemical and biological applications also appear promising: small tweezers might be useful to hold specimens (e.g., cells) in place while they are manipulated by other devices, such as injection needles. Drug delivery systems might be made small enough to be worn by patients, or even inserted into the body. Chemical processing that often uses complex lab equipment might be performed on a chip or wafer in a portable system. Biotechnology procedures normally performed in a batch process could be done on a cell-by-cell basis with greater control over the results.

At Lawrence Livermore Labs in California, researchers are working on spectrometers that could be used to monitor environmental hazardous materials. Lawrence Livermore is also developing a DNA sequencer on a chip. At least one major U.S. company is developing a gas chromatography system on a chip. Hitachi announced in 1989 that it had a prototype cell fusion system[31] that fused as many as 60 percent of cells compared with about 2 percent using conventional techniques.

Looking even further into the future, "microrobots" might be fashioned from micromechanical components. These tiny robots could perform a variety of functions. One of the objectives of the MITI micromechanics program is to develop microrobots that would be capable of inspecting inaccessible or hazardous locations such as in jet engines, nuclear plants, and the human body. Here in the United States, similar research is being conducted at NASA's Jet Propulsion Laboratory and a few universities. The objective of the NASA program is to make microrobots and microrovers useful for exploration of other planets and the moon.

[28] "Techniques include extrusion, diamond-point machining, and EDM (electro-discharge machining).

[29] Small motors of this type are already being used for drug delivery for livestock.

[30] Phillip Barth, Hewlett Packard, personal communication, May 29, 1991.

[31] Cell fusion is a technique used t. create cells capable of producing large quantities of monoclinal antibodies.