Chapter 1

Introduction and Summary

"Small is Beautiful." The truth of that statement is debated in economic and sociological circles, but when it comes to technology, there is no debate; small is beautiful because small is fast, small is cheap, and small is profitable. The revolution begun by electronics miniaturization during World War II is continuing to change the world and has spawned a revolution in miniaturized sensors and micromechanical devices.

Miniaturization plays a major role in the technical and economic rivalry between the United States and its competitors. It translates to market share and competitive advantage for many commercial and scientific products. Those companies and nations that can successfully develop and capitalize on miniaturization developments will reap handsome rewards. Personal computers, portable radios, and camcorders are examples of products that created massive new markets through miniaturization: they added billions of dollars to the GNP of countries where they were designed and built.

FINDINGS

The United States remains strong in miniaturization technologies research and development (R&D), although the lead over other nations is less substantial than it has been in the past.

U.S. researchers continue to innovate and produce world-leading research despite strong research programs in Japan and Europe. There are some areas where Japanese or European research surpasses the United States in quantity and in a few cases in quality as well. But on the whole, U.S. researchers lead in miniaturization technology R&D. The danger is that U.S. companies will lag other nations in implementing advanced technologies, especially when new technology is driven by a product or market dominated by another nation's industry.

The trends in silicon electronics miniaturization show no signs of slowing in the near future.

The current pace of miniaturization will produce memory chips (dynamic random access memory, DRAM) with a billion transistors and the capacity to store 1 billion bits (1 gigabit) of information around the year 2000.[1] Transistors will continue to shrink until the smallest feature is around 0.1 micron (1 micrometer or one millionth of a meter). By comparison, today's most advanced mass-produced integrated circuits have features as small as 0.8 microns. A human hair is 50 to 100 microns in width (see figure l-l). Achieving such tiny features will require a huge engineering and research effort. New fabrication equipment and processing techniques must be developed, pushing the cost of chip fabrication plants to over $1 billion, compared to hundreds of millions for a current state-of-the-art plant (see figure 1-2). It is likely that despite the high costs, chips having features around 0.1 micron will be manufactured; progress beyond the era of O.l-micron transistors is uncertain.

The technology of semiconductor manufacturing is being applied to other fields to create new capabilities. Sensors created with semiconductor manufacturing technology hold the promise of widespread applications over the next 10 years.

Micromechanical sensors for pressure and acceleration have used semiconductor manufacturing technology for several decades now, but recent innovations allow further miniaturization, greater flexibility, and compatibility with microelectronics. A wider range of sensors can now be fabricated using micromechanical structures.

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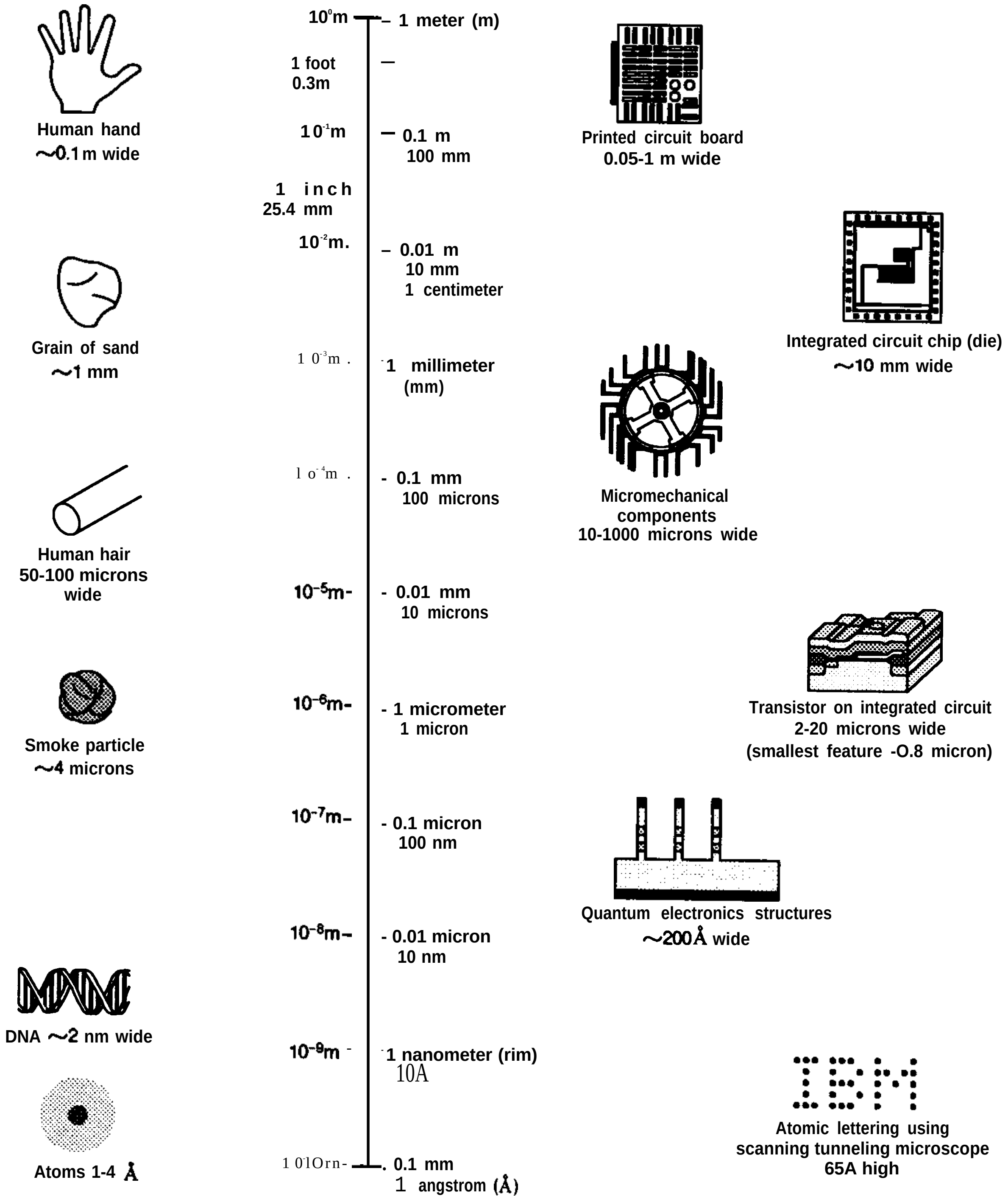
[1] This compares to today's most dense memory chips, which have about 4 million transistors and hold 4 million bits (4 megabits) of information.

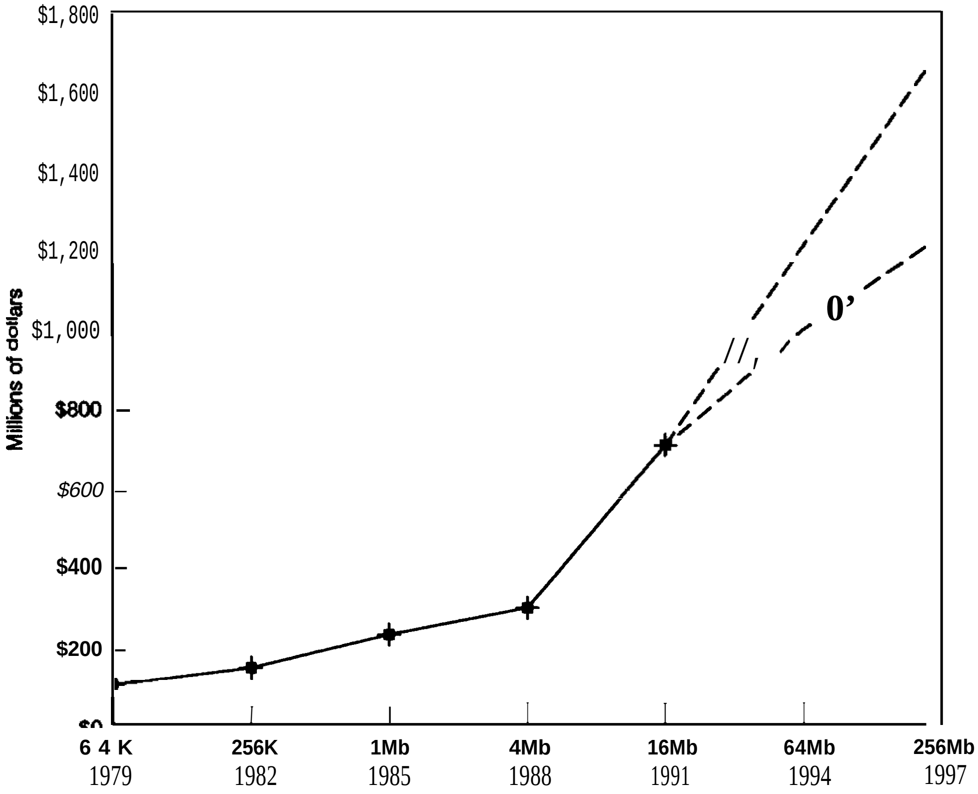
Figure 1-1 -How Small Is Small?



Each increment on the vertical scale indicates change in scale bye factor of 10. On the right of the scale are examples of miniaturization technologies. For comparison, several objects of similar scale are shown on the left.

SOURCES: Office of Technology Assessment, 1991. Data from Philip Morrison, *Powers of Ten (San* Francisco, CA: Scientific American Books, 1982); David Michael Freifelder, *Molecular Biology* (Portola Valley, CA: Jones and Bartlett Publishers, 1987), p. 183; Douglas M. Considine, cd., Van *Nostrand's Scientific Encyclopedia (New* York, *NY: Van Nostrand* Reinhold Co., 1983).

Figure 1-2–Cost of a New Memory Fabrication Facility (DRAM Fab)



SOURCE: Dataquest (August 1991) and Graydon Larrabee, Texas Instruments, personal communication, Sept. 18, 1991.

Biosensors and chemical sensors that can sense gases and chemicals are being perfected using integrated circuit manufacturing techniques and will be used in medical, food processing, and chemical processing applications. The economics of microelectronics fabrication will result in these new sensors becoming cheap and ubiquitous since hundreds or thousands can be created on a single wafer. Integrating sensors with electronics promises to increase the versatility of sensors for consumer, medicine, automotive, aerospace, and robotics markets.

Materials and surface science research is critical to further advancement of all miniaturization technologies.

In every miniaturization technology-from silicon microelectronics to quantum electronics, to micromechanics and biosensors—better understanding of materials and surface interactions will be a critical part of further technology advances. Better characterization of manufacturing processes will be necessary to make future generations of miniaturized semiconductors. Making practical miniaturized biosensors and chemical sensors will require better understanding of how to bond molecules to surfaces. Progress in micromechanics will depend on how well the mechanical and surface properties of materials like silicon are understood. Resolving problems in quantum electronics and molecular computing—the frontier of electronics miniaturization-are highly dependent on improved understanding and control of materials and surfaces. Basic research on material properties and surface interactions—especially in semiconductor processing and manufacturing-will be necessary for further miniaturization in many technology areas.

Packaging is playing an increasingly larger role in miniaturization of electronics.

Trends in miniaturization are creating pressure in the electronics industry to improve packaging:

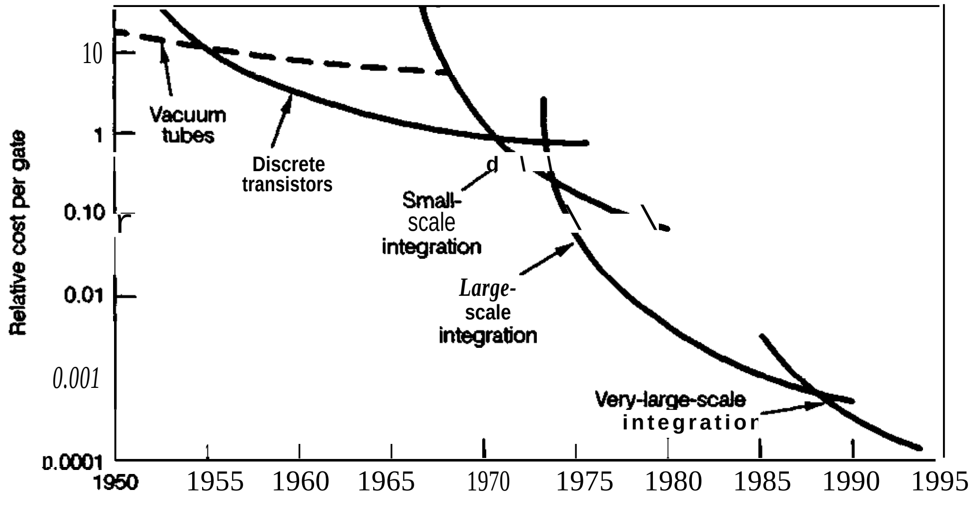
1. The proliferation of electronics into portable devices, consumer electronics, automobiles, and industrial applications is forcing more compact and ruggedized packaging;
2. The miniaturization of transistors causes them to operate faster and is forcing attention to better packaging because fast electronics must be packed close together to avoid delay in sending signals from chip to chip; and
3. As the costs of integrating more and more transistors onto the same piece of silicon increase, alternative ways to integrate transistors into a single package, such as multichip modules and surface mount technologies, are becoming more attractive.

WHY IS MINIATURIZATION IMPORTANT?

Miniaturization has inherent advantages, among them higher speed, lower cost, and greater density. Smaller electronics devices are generally faster because the signals do not have to travel as far within the device. Packing more functionality into a smaller or same-sized device reduces the cost of electronics. For example, a 1-megabit DRAM chip has four times the memory capacity of a 256-kilobit DRAM, but costs only about twice as much and occupies the same space as the lower capacity chip. Since the number of components (e.g., chips) on a circuit board largely determines the cost of the system, every 1-megabit DRAM used instead of four 256-kilobit DRAM reduces the number of memory chips on a board and reduces cost. Similarly, decreasing transistor size and greater integration has caused the price of logic devices to decline (see figure 1-3).

Miniaturization is important because it can create new markets by enabling new applications. Development of the microprocessor-a tiny com-

Figure 1-3-Price History of Electronic Logic



The price per gate-a circuit that performs a simple logic function -has continued on a steep downward trend since the introduction of the integrated circuit.

SOURCE: Adapted from John S. Mayo, “The Role of Microelectronics in Communications,” *Microelectronics* (San Francisco, CA: W.H. Freeman & Co., 1977), p. 106. Copyright(c) 1977 Scientific American, Inc. All rights reserved. Additional data from Graydon Larrabee, Texas Instruments, personal communication, Sept. 30, 1991.

puter on an integrated circuit—in 1970 led to a still expanding personal computer market currently valued at $70 billion per year. Flat panel displays and improved chip packaging have led to battery-powered portable personal computers the size of notebooks (and some even smaller—the size of a checkbook), one of the newest markets created by miniaturization. Personal communications is a developing major consumer market created by miniaturization. With the simultaneous reduction in the size of personal computers and cellular telephones, the two are merging into a cordless appliance that can communicate with the rest of the world through a network. Nippon Electric Co. (NEC) already offers a laptop computer with a built in cellular phone for sale in Japan; similar products are under development by American companies.

COMPETITIVENESS OF U.S. MINIATURIZATION TECHNOLOGIES

The competitive position of U.S. R&Din miniaturization technology remains strong, although competition from Japanese and European industry and governments has increased. As a result, the U.S. lead is less substantial than it was in the past. The rejuvenation of postwar Japanese and European economies has resulted in greater quality and quantity of research in those nations. There are now many more sources of competition in research worldwide.

Although U.S. R&D strength is still sound, U.S. industry has a mixed record in the implementation of miniaturization technology. Many miniaturization technologies that are crucial to the success of consumer electronics, for example, were embraced by Japanese industry more quickly than by U.S. industry. Surface mount technology, which allows more electronic chips to be placed on a circuit board, has had greater penetration into Japanese industry than U.S. industry (see figure 1-4). Concerned with packing more electronics into portable consumer products, e.g., cameras, calculators, and stereo receivers, Japanese consumer electronics companies were eager to reduce the size of their products. U.S. companies that produce computers, industrial controls, and other large systems serve markets that are not as concerned with size and portability.

Semiconductor

Shrinking the size of transistors and their interconnections is being pursued vigorously by U.S. industry, government, and universities. The mainstream approaches to transistor miniaturization use silicon with designs similar to those of past devices. In many respects, the United States leads world research on smaller transistors. Design of miniaturized transistors draws heavily on basic sciences and computer modeling, areas in which the United States remains strong. Implementing smaller transistors in products, however, is a strength of Japanese industry. DRAM chips have historically been the first commercial products produced with each new generation of semiconductor manufacturing equipment. Since DRAM chips are made primarily by Japanese companies, they are the leaders in implementing small transistors in products.

R&D in semiconductor technology is done primarily by industry in both the United States and Japan. The Federal Government spends about $0.5 billion per year on semiconductor R&D.[2] Japanese merchant semiconductor firms, companies that sell chips to other companies, have been outspending U.S. merchant firms on R&D (see figure 1-5). Total U.S. and Japanese industry R&D spending is roughly equal; $3.7 billion is spent in the United States and $4 billion in Japan.[3]

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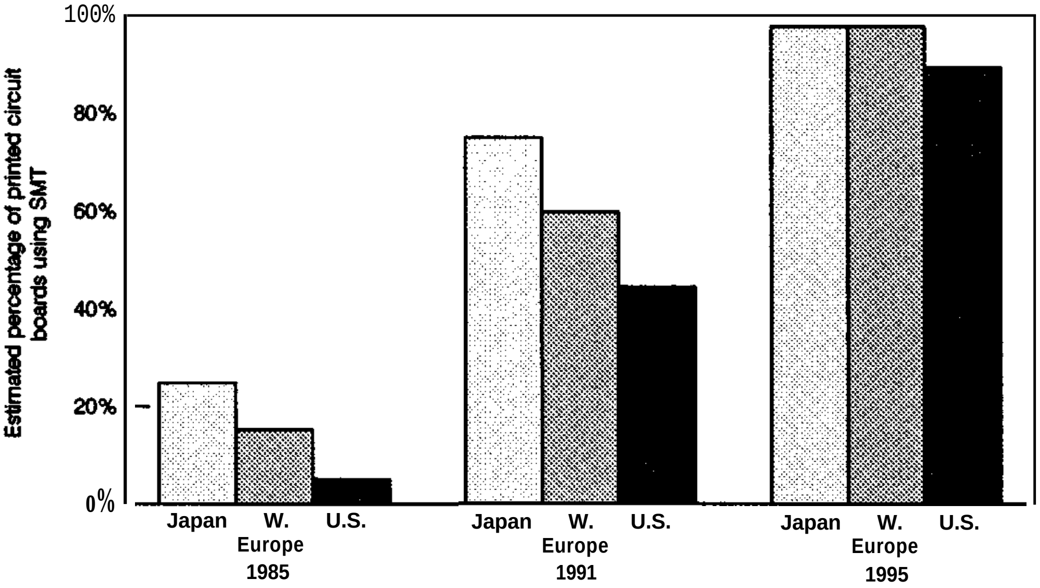
[2] Office of Management and Budget estimates for fiscal year 1990.

[3] Dataquest estimates for 1990.

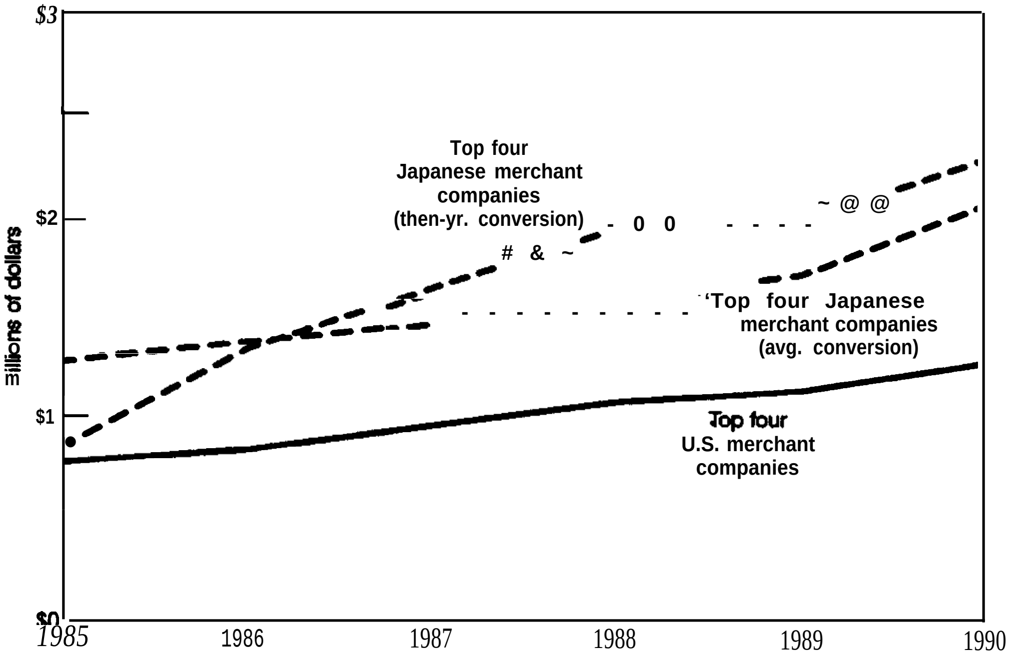
Figure 1-4-Use of Surface Mount Technologies



Use of surface mount technologies (SMT), which can reduce the thickness and volume of electronic products, has lagged in the United States compared to other nations. This graph shows past, current, and projected estimates of SMT use on printed circuit boards for Japan, Western Europe and the United States.

SOURCE: Office of Technology Assessment, 1991. Data from VLSI Research, Inc. (Fall 1991).

Figure 1-5-Semiconductor R&D Spending-Top Four Merchant Companies in the United States and Japan



U.S. semiconductor merchant companies are outspent in R&D by Japanese merchant firms. There are two curves for Japanese spending. The more dramatic increase results from converting yen to dollars at annual conversion rates. The other curve accounts for changes in the exchange rate by using a single conversion rate averaged over 5 years.

SOURCE: Office of Technology Assessment, 1991. Data from Dataquest.

Quantum Effect Devices

Significant momentum is left in the current trend in silicon miniaturization. But what happens when today's silicon designs hit physical limits in further miniaturization, as many experts expect will happen in about 10 years? One option will be to change the way switching devices (used to make computer logic) are made. Several alternative approaches are being pursued by the United States, Japan, and Europe. One approach—quantum effect electronics—is still are-search topic, but is receiving worldwide support. In the United States, about $8 million are spent annually by the Federal Government in this area. Most of the research is being sponsored by the Defense Advanced Research Project Agency (DARPA), with significant efforts at other DoD research agencies and the National Science Foundation (NSF). Industry support for this basic research is sparse; AT&T Bell Laboratories and Texas Instruments both have research activities in the area. IBM has a small research effort as well. Most of the research in the United States is being conducted at universities supported by government agencies.

The United States leads in research related to quantum effect devices, but this lead competes with other nations' efforts. Japanese efforts are significant and are beginning to make an impact; the Japanese involvement at recent conferences has grown. The United States can expect to maintain its lead in research, but, as the research moves toward development and implementation, the competition with Japanese researchers and corporations grows more fierce. Japanese industries have the advantage of being the world leaders in semiconductor processing technology and optoelectronics technology.[4] U.S. companies have the advantage of proximity to the world's leading researchers in the field. The Japanese Government will spend less than $3 million in fiscal year 1991 on quantum effect device research. With two new projects initiated in 1991 and 1992, funding will increase to about $6 million per year over the next 5 years. Japanese industry is actively pursuing quantum effect device research. Fujitsu and NTT have the two largest research efforts. Estimates of Japanese industrial investment in the field are difficult to confirm, but the sum may be more than double the government investment. The Ministry of International Trade and Industry (MITI) 1992 Large Scale Program, "Angstrom Technologies," will also fund research in quantum electronics. The program will spend 25 billion yen ($183 million) over ten years to conduct research on technologies at the scale of angstroms. It is not known, however, how much funding will go to quantum electronics.

Molecular and Biological Computing

One proposed way to continue the miniaturization of computers is to use individual molecules as switching devices in place of today's semiconductor transistors. U.S. investment in research related to molecule-based computing has diminished substantially since a period of intense interest in the early 1980s. NSF was the principal funding source for much of the original research. NSF's current funding for molecule-based computing is a few hundred thousand dollars and may end next year. Funding from U.S. industry is limited to a few venture capital firms and Digital Equipment Corp. Much of the effort in the United States has turned to development of molecular or biologically derived materials for applications in computing-related areas. For example, films of molecules rather than individual molecules[5] are being considered for use in optical disks and other data storage technologies.

Japanese and European governments continue to fund molecular computing research. However, differences in terminology complicate comparisons of programs between countries. Portions of one of the Japanese Exploratory Research for Advanced Technology (ERATO) projects are designed to pursue molecule-based com-

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[4] Many current applications for superlattices—a structure used to create quantum effect devices—involve opto electronics.

[5] Films of bacteriorhodopsin, a light sensitive biological molecule, are being prepared by researchers at Syracuse University, Mitsubishi, and a few American companies.

puting[6] and the Ministry of International Trade and Industry (MITI) Basic Technologies for Future Industries Program spends about 300 million yen ($4 million) on research for biological molecular computing.

Packaging and Interconnection

As electronics become more ubiquitous, faster, and denser, the pressure on improving electronic packaging technology will increase. Federal funding has not addressed the issue of packaging as a whole, but many different programs fund research on packaging. Technologies such as surface mount technologies (SMT) and multichip module (MCM) technology can place more semiconductor chips into a system than traditional packaging. SMT is maturing and is seeing widespread application. Over 50 companies and research institutions worldwide are now pursuing MCM or related technology.[7] One focus of the Microelectronics and Computing Technology Consortium (MCC)–a consortium of U.S. companies—is packaging and interconnection technology, including MCM technology. A National Research Council report in 199@ found that the American and Japanese industries are about equally matched in printed wiring boards, multichip modules, and other interconnection technology. The report also found that U.S. industry was dependent on Japanese suppliers for materials required for several packaging technologies.

Biosensors and Chemical Sensors

There is intense worldwide interest in developing biosensors and chemical sensors, particularly in Japan. Biosensors can detect the presence of chemicals or molecules such as glucose, urea, and oxygen. Diverse applications are seen in medical diagnosis, industrial process monitoring and control, fermentation process control, and food quality monitoring. Most of the R&D is being done by industry. Within the Federal Government, the Department of Defense (DOD) is a primary supporter of biosensor R&D with the National Institutes of Health supporting some development.

According to a 1989 Japanese Technology and Evaluation Center (JTEC) Panel report, the U.S. efforts in chemical and biological sensors trail those of Japan.[9] The panel report rated Japanese efforts more advanced in commercialization, product development and quantity of basic research. In quality of research, the U.S. and Japanese efforts were considered equal. OTA interviews in the biosensor industry indicate the situation has not changed much since the JTEC report. According to the report, in 1985 there were more Japanese publications and patents for biosensors than U.S. publications and patents.[10] A consortia has been established by 35 Japanese companies to conduct R&Din biological sensors. The annual budget for the consortia is about $2 million from industry matched by funds from the Ministry of Agriculture, Forestry and Fisheries.[11] In addition, a large number of Japanese companies are funding independent development of biosensors.[12]

Micro-Mechanical Systems

Development of new manufacturing techniques by researchers at American universities during the 1980s has led to an expansion of interest in micromechanics around the world. Build-

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[6] Kunitake molecular architecture project *(1987-92).*

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

[8] National Research Council, Commission on Engineering and Technical Systems, National Materials Advisory Board, *Materials for* Hi@ *Density Electronic Packaging and Interconnection* (Washington, DC: National Materials Advisory Board, March 1990).

[9] U.S. Department of Commerce, "JTECH (Japanese Technology Evaluation Program) Panel Report on Advanced Sensors in Japan," January 1989, p. 184.

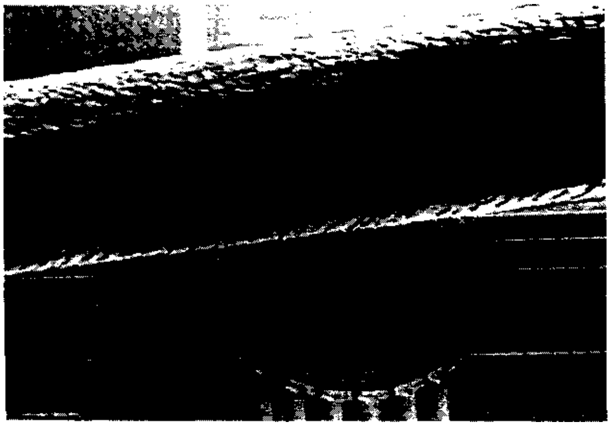
[10] Publications: 59 Japan, 35 United States; patents: 74 Japan, 9 United States.

[11] *High Technology Business,* September-October 1989, p. 29.

[12] National Science Foundation, Japanese Technology and Evaluation Center (JTEC), Viewgraphs for "JTEC Workshop on Bioprocess Engineering in Japan" (Washington, DC: National Science Foundation, May 21, 1991); and U.S. Congress, Office of Technology Assessment, *Biotechnology in a Global Economy,* OTA-BA-494 (Washington, DC: U.S. Government Printing Office, October 1991).

ing upon established semiconductor processing techniques, researchers have been able to fabricate elaborate mechanical structures: motors and turbines as wide as a hair (see photograph), cantilevers capable of measuring acceleration, and gear assemblies smaller than a fleck of dust. These new techniques are closely related to techniques traditionally used to create mechanical structures for use as pressure sensors. The first applications with sizeable markets for the new technology are in sensors and instrumentation. Future applications may involve micromechanical actuators or systems of actuators and sensors. Some niche applications are already using micromechanical actuators made with conventional milling and extrusion techniques (non-microelectronics techniques).

Researchers at U.S. universities are the acknowledged leaders in micromechanical sensor research. The European nations, especially Germany, have a strong technology base in sensor technology and are supported with extensive government funding. Germany's Karlsruhe Nuclear Research Center and Fraunhofer Institute codeveloped a new lithographic process for making relatively thick (hundreds of microns) micromechanical structures, called LIGA. Although their industrial research in pressure and acceleration sensors is impressive, the Japanese trail the United States and Europe in R&D.



Pho credit: Berkeley Sens and A C

A micromoto hown with pe mposed man ai

Although still relatively modest in scale, in the last few years funding for micromechanics has been increasing rapidly. In the United States, research in the field is sponsored by several different agencies, including DOD, NSF, the National Institutes of Health (NIH), the National Aeronautics and Space Administration (NASA), and the Department of Energy (DOE). Total Federal spending in the field is planned to be over $15 million in 1991-from under $6 million in 1990 and 1991. DOD and NSF were early supporters of the technology. DARPA has been spending about $2 million per year, and plans to spend about $3 million per year in 1992. NSF has been funding much of the research at universities since 1983 at about $2 million per year. Efforts at the DOE have been mostly at Sandia and Lawrence Livermore National Laboratories. Starting in 1991, DOE will spend about $16 million over 3 years at Louisiana Technical University (LTU) as directed by Congress. Other State governments including California and Louisiana have shown interest in promoting micromechanics research.

On the whole, U.S. industry is playing "wait and see" while trying to sort out what commercial applications the technology might have. Sensor and instrumentation companies, however, see clearer potential for applications and are pushing forward more aggressively. Analog Devices, Inc., for example, has developed the first commercial product that uses the new manufacturing technique—an acceleration sensor targeted for automobile airbag deployment applications. Other companies are abandoning micromechanics. A pioneer in the field, AT&T Bell Laboratories, terminated its efforts in micromechanics. U.S. industry spent over $20 million in fiscal year 1991 on micromechanics R&D.

In Europe the largest and most advanced research efforts are being pursued by Germany. In 1990, the Germany Federal Ministry for Research and Technology initiated a 4-year program that will spend 400 million marks ($230 million) on research. The German Government recently announced it will extend the program for at least another year. The Karlsruhe Nuclear Research Center and the Fraunhofer Institute are conduct-ing leading research in micromechanics. The Fraunhofer Institute is designed to encourage participation from industry and receives about 50 percent of its funding for micromechanics from industry. A consortium of German companies has licensed technology from Karlsruhe and is developing industrial applications based on the technology. Germany companies are interested in applications of the technology. Bosch has the largest effort, and Siemens and Messerschmidt also have significant R&D efforts in the field.

Other European nations and industries are also pursuing micromechanics research. The most notable research efforts besides Germany are in Switzerland and the Netherlands. The Institute of Microelectronics in Neuchatel, Switzerland, is developing solid-state sensors and is active in the field of micromechanics research. The University of Twente and the University of Delft in the Netherlands are active in the field, with a new institute formed at the University of Twente—the Micro-Electromechanical Sensors and Actuators (MESA) Institute. Almost every nation in Europe has research activity in micromechanics—much of which is at universities.

Perceiving themselves as behind in micromechanics research, Japanese researchers are vigorously pursuing the technology with a new MITI program that will spend 25 billion yen ($183 million) over the next 10 years. The program, initiated in April of 1991, aims to develop microrobots for health and industrial applications. Micromechanical systems will be a major part of the program's research, although portions of the program will bean extension of a previous MITI program to develop miniature robots. Fiscal year 1991 funding for the program is only about $3 million, but that will increase to over $20 million annually as the program accelerates to full speed. Japanese industry typically adds its own investment of labor and equipment to work sponsored by MITI, so the total research effort associated with this program is substantially larger than the government investment. In addition to the MITI program, the Japanese Science and Technology Agency (STA) funds research at several universities in Japan, including the University of Tokyo,[13] at a total of about $1 million per year. Japanese industry is pursuing research in the field, with 1991 expenditures estimated at over $20 million. One of the largest industrial research efforts is at Toyota's central R&D facility in Nagoya. Other industrial research is underway at NTT, NEC Corp., Ricoh Corp., IBM-Tokyo, and Matsushita Central Research. The MITI project has increased the interest of industry in micromechanics, and R&D can be expected to increase over the next several years.

Fabrication Technology Research and Development

Making miniaturized electronics, sensors, and micromechanics requires increasingly sophisticated manufacturing equipment as each generation of miniaturized components demands greater precision in fabrication.

Lithography—the technique used to etch features into integrated circuits—is one of the most challenging hurdles for future miniaturization of integrated circuits. The size of a transistor, the lines connecting transistors, and other devices in a circuit can only be made as small as the resolution of the tools used to make them. As the size of transistors become smaller, making tools of adequate resolution becomes increasingly difficult and more expensive. The current approach to increasing the resolution of lithography has been to reduce the wavelength of the light source, progressing from visible wavelengths, to ultraviolet, to deep ultraviolet. Now many experts are predicting that the trend will continue to x-ray lithography, but the outcome is far from certain. Some experts predict ultra-violet lithography will be useful in creating features as small as those possible with x-ray lithography. Using a technique called phase–shifting, this approach would require very sophisticated masks and computer software to be successful. Other lithographic ap-

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[13] Others include Tohoku University, University of Osaka Prefecture, and Kyushu University.

preaches such as electron-beam and ion-beam are considered viable options.

The debate surrounding x-ray lithography has been well documented.[14] The governments and industries of the United States, Japan, and European nations are all investing heavily in R&D for the next generation of lithography tools. Congress allocated $60 million to DARPA in fiscal year 1991 to develop x-ray lithography technology, including research on mask development and laser x-ray sources. There are a total of five synchrotrons currently in the United States for lithography research. Two more will come on line by 1993 in Baton Rouge, Louisiana and Upton, New York. Industrial support for x-ray lithography using synchrotrons consists primarily of IBM and Motorola. AT&T is focusing on x-ray lithography using laser sources instead of synchrotrons. In Japan and Germany, government and industry are taking an aggressive approach to x-ray lithography development. There are nine synchrotrons in Japan and two synchrotrons in Berlin for lithography research.

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[14] For example, see Mark Crawford, "The Silicon Chip Race Advances Into X-rays," Science, vol. 246, Dec. 15, 1989, pp. 1382-1383; U.S. Congress, Congressional Budget Office, *Using R&D Consortia for Commercial Innovation: SEMATECH, X-ray Lithography, and High-Resolution Systems* (Washington, DC: Congressional Budget Office, July 1990), pp. 69-87; U.S. Congress, Senate Committee on Commerce, Science, and Transportation, Subcommittee on Science, Technology, and Space, *Semiconductors and the Electronics Industry*, Serial No. 101-771, May 17, 1990; and John Markoff, "Etching the Chips of the Future," *New York Times*, June 20, 1990, p. D1.