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RESEARCH & DEVELOPMENT

BACKGROUND PAPER

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Foreword

Microelectronics, the fundamental! building block of today's pervasive information technologies, has progressed at a tremendous rate over the last few decades and has become a vital part of U.S. commerce and defense. This fast-changing field depends critically on aggressive research and development (R&D) programs. Federal participation in microelectronics R&D is twofold: the government directly funds a significant fraction of the activities, and several Federal policies indirectly affect private support of R&D. Hence, Congress has a major role to play in microelectronics R&D—a role that can be illuminated by a better understanding of today's activities in this area.

In November 1984, the House Committee on Science and Technology asked OTA to prepare a background paper on microelectronics R&D as a follow-on to the OTA assessment of *Information Technology R&D: Critical Trends and Issues,* released in February 1985. This background paper describes the current state of research and development in microelectronics by examining the range of R&D efforts and the sources of Federal and private support for R&D. It also presents potential policy concerns that stem from existing arrangements for direct Federal support and from changes underway in microelectronics R&D.

Many members of the diverse microelectronics community, spanning the spectrum from basic research to applied development, contributed their knowledge, insight, and viewpoints to this background paper. These included scientists, engineers, managers, and observers in Federal agencies and laboratories, industry, universities, and other organizations. OTA is pleased to thank all participants for their assistance. However, OTA assumes full responsibility for the contents of this study.

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Chapter 1

Issues in Microelectronics Research and Development

Microelectronics is the cornerstone of the information technologies that pervade virtually every aspect of contemporary life. These computer and communications technologies are the basis for changes such as automation, energy conservation, and pollution control in offices, factories, automobiles, and homes; supercomputers for applications from weather prediction to computational research; new capabilities in financial services; new means of storing and playing back audio and video recordings; advanced telephone and television systems; and complex weapons systems for national defense. Each of these areas is critically dependent on microelectronics technology. Furthermore, the microelectronics industry—and the industries that depend on it—are vital to the U.S. economy.

Research and development (R&D) efforts have fueled progress in microelectronics technology at an extraordinary rate. Since the invention of the integrated circuit (IC) 27 years ago, the capabilities of these devices have more than doubled every 2 years. Currently, an IC with several hundred thousand components can be purchased for a few dollars-less than the 1950's price for a single component.

The Federal Government has historically played vital roles, some direct and some indirect, in microelectronics research and development. These multiple involvements make it important to understand both the structure of institutional support and the implications of current technological trends in considering the many Federal policies that affect microelectronics R&D.

Today, many factors, including shifts in industry structure and limitations posed by technological trends, raise questions concerning the types and levels of Federal support for microelectronics R&D. To address these issues, this OTA background paper, requested by the House Committee on Science and Technology, describes the current state of microelectronics research and development by examining the technologies emerging from R&D efforts and the range of institutional support for R&D. Although other relevant Federal policies are discussed to some extent, the primary focus of the paper is the role of direct Federal support for microelectronics R&D.

This chapter: 1) summarizes the OTA findings, and 2) discusses potential Federal policy implications that they suggest.[1]

MAIN FINDINGS OF THE STUDY: TRENDS IN MICROELECTRONICS R&D

Findings About Institutional Support

A broad range of organizations supports microelectronics R&D. In the United States, Federal agencies and laboratories, private films, cooperative research organizations, and universities all contribute in different ways to progress in the field. Among international activities, Japanese R&D efforts predominate; several European nations also support microelectronics research and development.

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[1] In this paper, the term "microelectronics' is used to describe miniature electronic devices in general, Readers whose background in the technology is limited may wish to review app. A before proceeding.

Within the Federal Government, the Department of Defense (DOD) sponsors the largest share of microelectronics R&D. Federal funds from various sources support work in Federal laboratories, industry, universities, and cooperative organizations.

Private sector R&D in the United States encompasses a spectrum of activities in both vertically integrated companies and merchant firms.[2] Vertically integrated companies generally support a full range of activities from basic research to applied development, although the types and levels of R&D vary widely from company to company. Merchant firms tend to limit their R&D to the last stages of development. Some companies in each category support and participate in R&D in cooperative organizations and in universities in addition to their onsite efforts.

OTA identified four basic changes occurring in institutional support for microelectronics R&D in the United States:

1. In the last few years, many factors have converged to alter the structure of the microelectronics industry. Chief among these is the Japanese challenge to U.S. competitiveness, which has led to increased shares of U.S. and international markets for Japanese companies and, consequently, reduced profits for U.S. companies. This may be leading to decreased R&D efforts by the industry.
2. The exceptional capability of Japanese companies to transform research concepts into products is well established in microelectronics. Now, there is also growing evidence that Japanese basic research efforts are outpacing U.S. efforts in some areas of microelectronics, e.g., optoelectronics.
3. Because of international competition and limited resources for equipment and personnel, cooperative research efforts are gaining popularity as a means to bolster R&D. These activities, which typically involve cooperation among different industrial, academic, and Federal organizations, represent a relatively new approach to R&D in the United States.
4. The deregulation of the telecommunications industry is affecting R&D in microelectronics-related areas. AT&T Bell Laboratories' efforts are becoming more closely tied to products than were research efforts at the predivestiture Bell Laboratories. The role of Bell Communications Research is still not completely known.

Findings About Technological Trends

Microelectronics can be separated into two related parts: 1) fabrication technology, including materials, devices, and circuits; and 2) chip architecture or design. Advances are taking place in both aspects of the technology.

Trends in Fabrication Technology

Over the next two decades, the primary technological trend in the physical structure of microelectronics is likely to be continued miniaturization of silicon integrated circuits. Because this scaling down of the dimensions of ICs has been the key to better and less expensive **chips,** it has been the basis of progress in microelectronics over the last 25 years. OTA found that, according to experts, this trend will continue for the next 5 to 10 years and then will begin to level off in approximately 15 years, when minimum dimensions are between one-tenth and one-fifth of a micron-about one-tenth of the minimum size currently in production. (A micron is one-millionth of a meter. See figure A-3 in app. A.)

OTA identified several other technological trends related to this central finding. Development activities expected to influence the industry soon center on advanced manufacturing techniques required to fabricate circuits

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*"Vertically integrated" in this context refers to a company that makes microelectronics to use in the products that it sells, e.g., a computer company that makes integrated circuits for its computers. The microelectronics division of such a company is often termed a captive manufacturer. Some vertically integrated companies also sell their microelectronic products to others in addition to using them internally. A merchant firm, in contrast, makes microelectronics primarily to sell to other end users.

with smaller and smaller dimensions. These advances represent incremental changes in current silicon IC technology.

Mid- to long-term R&D efforts, which focus on significantly different technologies with promise for the next generation of microelectronics, are centered on:

- digital and analog (microwave) integrated circuits made from gallium arsenide (GaAs),
- optoelectronics, and
- quantum-effect structures.

OTA found that few microelectronics experts expect GaAs integrated circuits to replace silicon digital ICs. Rather, they believe that the two types of ICs will meet complementary needs.

The outlook for technologies based on materials other than semiconductors appears limited for the next few decades. R&D activities in Josephson junction technology, once a major contender for the next generation of ICs for computers, are currently receiving limited attention. Efforts in bimolecular electronics are only exploratory today, and their promise speculative. Most experts agree that they will not come to fruition in the next few decades, if ever.

Trends in Design

While circuits continue to shrink and begin to reach limitations, the power of design tools, and hence the flexibility of IC design, will continue to grow rapidly, OTA found. Users have been limited to building systems out of standard ICs and other components in the past. Now, complex new design systems coupled with advanced manufacturing capabilities allow users to configure chips to perform specialized tasks. Progress in this area will hinge on R&D activities in design software.

Merchant manufacturers are currently pursuing the expanding markets for application-specific ICs (ASICs), which include custom and semicustom chips. As the capabilities of design systems and the networks that link them to manufacturing facilities expand, an engineer will probably be able to design an IC for a specific need from a workstation, transmit the design to a silicon foundry, and receive the completed special chip within a short time and for low cost. This level of flexibility could open the door to a whole new genre of electronic capabilities.

POTENTIAL POLICY CONCERNS

The state of research and development in microelectronics raises several potential policy concerns about the Federal role. One set of issues arises from the changes occurring in microelectronics R&D; a second set centers on *ongoing* direct Federal support for microelectronics R&D.

Federal Response to Changes in Microelectronics R&D

Governmental policies need to recognize the changes underway in microelectronics, both in the industry's support of and need for R&D, and in the emerging technological trends.

Federal Response to Changes in the Industry

In the early days of the merchant IC industry, that part of the microelectronics community generally tried to minimize its interaction with the Federal Government. In recent years, however, changes in the industry have shifted the relationship between the government and merchant firms, making it necessary for each to attend more closely to the other: This signifies wider recognition of the impact of Federal policy on the industry and a resulting gem eral trend toward increased reliance on Federal policy by the industry.

Because Japanese competition is the greatest challenge-that U.S. merchant microelectronics companies face today, it is the focal point of interactions between the industry and the Federal Government. The U.S. industry has, in the last few months, asked the government for help in changing the trade imbalance in three separate cases.[3] Another pressing concern is the high cost of capital in the United States relative to Japan.

The current problems that the U.S. companies face pose a paradox. Although R&D, a long-term investment, *cannot* solve industry's immediate problems, it is a crucial ingredient in industrial competitiveness. Without continued strength in R&D, solutions to the near-term problems will only delay the decline of the U.S. companies. Yet microelectronics firms that are struggling to survive are likely to neglect R&D activity in the face of more immediate and pressing problems. For example, they may find it difficult to justify funding R&D while cutting jobs at an unprecedented rate. This may lead to a deterioration of the industrial R&D base.

Federal policies that affect the amount of R&D available to private companies can be categorized as follows:

- policies that generally strengthen the companies by making them more competitive, and thus assuring sufficient profits to support R&D (e. g., international trade policies and mechanisms to lower capital costs);
- policies to ease the financial burden or lower the risks of private R&D (e.g., the tax treatment of R&D[4] and intellectual property protections); and
- direct Federal funding for R&D, the results of which are available to private companies.

The first two types of Federal involvement are indirect ways to make R&D investment easier for companies; the third approach funds R&D directly.

The lion's share of direct Federal support for microelectronics R&D comes from the Department of Defense, and is therefore driven by military requirements. In general, DOD-sponsored basic research serves both military and commercial goals. Development activities for military microelectronics, in contrast, do not overlap completely with activities for commercial needs. For example, low-cost, high-volume production capabilities are a high priority for the commercial manufacture of integrated circuits, but the major DOD program to advance IC technology, the Very High Speed Integrated Circuit (VHSIC) program, focuses on design and fabrication of a small volume of highly specialized ICs for use in military systems.

The DOD style for funding microelectronics R&D, characterized by long-term investment in R&D with a clear connection to end uses, appears to have been highly successful for achieving military goals. Some members of the microelectronics community would, therefore, like to see the Federal Government aim a similar level of support at commercial needs—a point of view that has gained momentum in the face of the current pressures on the industry. They cite the influential Japanese Ministry of International Trade and Industry (MITI) as a useful model. But opinions in the microelectronics community diverge sharply on this topic. Opponents of further direct Federal involvement in microelectronics R&D for the industry argue that the results of R&D will meet commercial needs and will be available to industry only if the commercial sector directs and carries out the work itself. They view the MITI model as unacceptable in the American context, given the vast differences in industry-government relationships between Japan and the United States.

One example of a plan to start to bridge this difference of opinion comes from the Semicon-

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[3] Semiconductor Industry Association, "Japanese Market Barriers in Microelectronics: Memorandum in Support of a Petition Pursuant to Section 301 of the Trade Act of 1974 As Amended," June 14, 1985; "Japanese Accused on Chips," New *York Times,* June 27, 1985, p. D1; and "EpROM Makers File Claim Against Japanese 'Dumping'," *Electronic News,* Oct. 7, 1985, p. 1.

[4] Since 1981, firms have been allowed tax credits on increased expenses for research and development, enhancing the R&D spending power of these companies. This R&D tax credit expired at the end of 1985.

[5] Pressure from the microelectronics industry spurred Congress to legislate a new form of intellectual property protection in the Semiconductor Chip Protection Act. The act, signed into law in November 1984, protects masks (used to fabricate ICs) from unauthorized copying, and so offers manufacturers an additional incentive to come out with new products by protecting returns on R&D investments.

ductor Research Corp. (SRC), a cooperative R&D organization directed by microelectronics industry leaders. SRC currently supports R&D at universities with funds from its member companies. In the next few years, it may ask the Federal Government to match this level of support. The doubled budget would be administered solely by SRC, which would soothe at least the concerns of SRC's member companies about the selection of research topics and the availability of results.6

Federal Response to Technological Trends

Limitations to growth that stem from technological trends are less immediate than the economic problems that the industry faces, but they too pose questions about the appropriate Federal role. The shrinking of circuitry on silicon chips, on which progress has hinged thus far, has required enormous innovation, chiefly in manufacturing technology and engineering exploitation of the concepts for transistors and circuit integration. But progress in fabrication technology beyond the limits of silicon scaling will demand a wider range of more basic R&D activities.

This technological factor may drive expanded Federal participation in R&D for potential alternative microelectronics technologies. This could take many forms, including policies to encourage basic research in industry or greater direct Federal R&D funding. Alternatively, Federal agencies may select specific areas in which to focus support without significantly increasing their total funding levels. Because the Federal Government funds a wide range of microelectronics research efforts and interacts with a variety of R&D organizations, it can exert considerable leverage in key areas. In these areas, some Federal agencies might be able to lead the way for efforts by participants in the commercial sector, universities, and other Federal agencies by targeting R&D monies.

This has already occurred in the case of GaAs digital integrated circuits research led by the Defense Advanced Research Projects Agency (DARPA). The microelectronics community had conducted relatively little research on integrated circuits made from gallium arsenide before 1982 when DARPA decided, based on the results of 6 years of GaAs basic research that they had sponsored, to fund a series of pilot production lines to demonstrate the feasibility of using GaAs for ICs. This announcement kindled the interest of a variety of organizations, and several defense electronics firms mobilized to build a base of activities in GaAs so that they could be involved with the pilot lines. Three new commercial ventures have already spun off from this work. Perhaps even more significantly, there is some evidence that DARPA's interest in GaAs ICs may have helped to convince research organizations such as AT&T Bell Laboratories that the field deserves an intensive research effort. At about the same time, IBM turned its focus for alternative chip technology from Josephson junctions to GaAs. In part because of DARPA's initiative, the activities in GaAs ICs grew in a few years from a handful of isolated efforts in individual laboratories to large programs sponsored by Federal agencies, industry, and universities.

Direct Federal Support for Microelectronics R&D: Policy Questions

Ongoing direct funding of microelectronics R&D from Federal agencies continues to raise policy concerns. The system of multisource support, with several different Federal agencies funding microelectronics R&D activities, poses potential policy questions. And since the largest amount of support comes from DOD, many of the concerns center on the implications of defense R&D spending.

Multiple Sources of Federal Funding: Pros and Cons

Microelectronics, like other science and engineering fields, receives R&D funding from several different Federal agencies. Because a Department of Science or some other scheme for

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‘Interview with George M. Scalise, Advanced Micro Devices and Semiconductor Research Corp., June 1985. The doubled budget could total as much as $100 million per year, although SRC's current annual budget is only approximately$15 million.

centralized R&D funding is proposed and considered from time to time, it is important to examine the pros and cons of the current multisource arrangement. In microelectronics-related areas, the system generally avoids potential pitfalls and offers advantages over a centralized system.

The potential drawbacks of the multisource system do not pose problems at present. One possible difficulty is wasteful duplication of effort and competition for resources if the various agencies do not communicate their plans to one another. The present system, too, could confuse or inconvenience researchers seeking funding, particularly newcomers. However, the researchers within an area typically communicate with each other and are familiar with the full range of activities in their area. These informal infrastructures prevent most unnecessary duplication of effort and alert researchers to the relevant funding sources in the area. In addition, the agencies coordinate R&D funding through both formal and informal channels.

The advantages of distributed funding across agencies more than compensate for the potential problems. The arrangement provides researchers with multiple channels for Federal support for promising new ideas; they can turn to a second agency if a proposal is refused by the first. The present system also permits each agency to fund R&D to meet its own goals or those of its parent department. The existing situation, with several loosely coordinated independent agencies funding different aspects of microelectronics R&D, appears to serve its purpose well.

Questions Raised by Department of Defense Activities

Beyond the questions of the balance between R&D for military needs and R&D for commercial needs, DOD activities raise two sets of potential Federal policy issues. These are:

1. DOD control of research and development, particularly university research activities; and
2. the impact of the Strategic Defense Initiative (SDI) on the structure of DOD microelectronics R&D.

Keeping information about new defense technologies within the United States is a critical concern for military security; free and wide exchange of ideas and results is an equally crucial ingredient in scientific research. This dilemma is the basis of an ongoing discussion among players both within and outside DOD, all of whom are trying to determine the appropriate type and level of control of defense research results. Controls on universities, where many foreign students are involved in scientific research on campus, are of particular concern. Some leading universities have banned classified research on campus altogether as a partial solution. Several years of debate recently resulted in a policy from the White House (the National Security Decision Directive) which makes classification the only mechanism for control of fundamental research (i.e., unclassified research may not be restricted).[8] The policy does not solve the problems completely. It will, however, greatly simplify the process of determining control by reducing the number of gray areas.

R&D funding under SDI raises two types of concerns about DOD research: the impact on the structure of DOD funding in microelectronics R&D, and further questions about the treatment of university research.

The initiative's activities in this area may involve a major restructuring of the funds for microelectronics R&D from the various DOD agencies, whether or not it increases the overall level of DOD support. The transfer of the GaAs IC pilot lines from DARPA to the SD I Organization (SD IO) is early evidence to support this possibility. Given the wide perception that the current arrangement for DOD-sponsored research (with several different agencies operating independently but commu-

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[7] Institute of Electrical and Electronics Engineers, "DOD's Perle Questions Value of Open Research on Campus," *The Institute,* July 1985, p. 10.

[8] "White House Issues Secrecy Guideline, " *Science,* vol. 230, Oct. 11, 1985, p. 152.

nicating with each other) works well, centralized funding of microelectronics R&D through SDIO could decrease DOD's effectiveness in the field.

The fact that SD I-funded activities are designated as "advanced technology development" rather than "research" has exacerbated the concerns about DOD controls on university research. There has been concern that DOD would censor dissemination of all SDI work, including university activities. From the perspective of a group of university scientists boycotting SDI, "the likelihood that SDI funding will restrict academic freedom . . . is greater than for other sources of funding. " (A recent policy stating that SD I research at universities will be considered "fundamental research, " which is to be treated in accordance with the new National Security Decision Directive, may have alleviated some of these concerns. [10]) On the other hand, the fact that SDI's Innovative Science and Technology Office received approximately 2,700 preliminary proposals from university researchers over a period of just 3 months[11] is strong evidence of interest from that community.

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[9] From the boycott petition, as quoted in "Star Wars Boycott Gains Strength, Science, vol. 230, Oct. 11, 1985, p. 152.

[10] Institute of Electrical and Electronics Engineers, " SDI Memo Bars Controls on Most 'Star Wars' Research in Universities, " *The Institute*, October 1985, p. 1,

[11] Dwight Duston, Innovative Science and Technology office, SDI organization, personal communication, January 1986. This number includes preliminary' proposals in areas other than microelectronics.

Chapter 2

Introduction: Microelectronics Technology and R&D

THE IMPACT OF MICROELECTRONICS AND EVOLUTION OF THE INDUSTRY

Microelectronics technology has dramatically improved the capabilities of computers and communications systems, while also fueling the growth of completely new applications, such as personal computers. Growing extremely fast and providing increasingly powerful and inexpensive tools to manipulate electronic signals, microelectronics has become the cornerstone of information technologies. It is central to such areas as:

- computers, from powerful supercomputers, through business computers, to inexpensive personal computers;
- communications systems, including switching stations and satellite communications;
- consumer products, such as electronic watches, video games, and pocket calculators;
- control systems for industrial applications, automobiles, and home appliances; and
- military systems for national defense.

Microelectronics has become a vital part of U.S. commerce and defense. In both sectors, maintaining a technological edge over the rest of the world is the only way to ensure security—whether military or economic. U.S. companies claimed approximately $14 billion of the $26-billion world market for microelectronics in 1984.[1] The development of increasingly sophisticated weapons systems means that virtually every aspect of current military technology depends on microelectronics.

The dramatic growth of the technology has prompted observers to describe it as the microelectronics revolution. To date, the miniaturization of circuitry, which leads to products that perform faster and better, has been chiefly responsible for this revolution. Shrinking the electronic devices has yielded lower cost, expanded performance, and higher reliability. By any measure—cost for a given function, complexity of circuits, performance—integrated circuit (IC) technology has progressed at a tremendous rate since its inception. In 1964, Gordon E. Moore predicted that the number of components on a chip would continue to double annually, as it had since the beginning of that decade. Twenty years later, technology has not departed significantly from Moore's law. Experts predict a slowing of the trend over the next 10 to 20 years.

At the same time, IC design will begin to alter the way that system engineers use ICs. New capabilities provided by design software, silicon foundries, and the networks that link them allow the end user much greater flexibility in designing chips for a specific application. This trend, coupled with changes in fabrication technology, will affect the industry.

Many other factors, more immediate than the scientific and engineering changes, affect the structure of the American microelectronics industry, especially merchant firms. These include international competition, capital requirements, capital cost, and shifting markets. U.S. microelectronics companies currently face debilitating competition from Japanese sources, and other Asian countries (e.g., Korea) are also preparing to enter the market. At the same time, the industry is growing stead-

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[1] "The Japanese Semiconductor Market and S1A's 301 Petition," presentation by George Scalise for the Semiconductor Industry Association, July 24, 1985.

ily more capital-intensive, since every technological advance demands more complex equipment and production facilities. The high cost of capital exacerbates this problem. Finally, although many of the markets for uses of microelectronic products are growing, some of them grow explosively and then plummet as rapidly, as did the video games market. These shifts cause instability in the industry.

Together, these technological, international, and economic trends and forces are altering the microelectronics industry. The changes mark the beginning of the maturing of the industry and may signal the beginning of the end of an era of apparently limitless growth.

THE NATURE OF RESEARCH AND DEVELOPMENT IN MICROELECTRONICS

Since microelectronics has expanded swiftly and will continue to do so, research and development (R&D) activities play an extremely crucial role in its progress. As the technology and the industry mature, however, the reasons for supporting R&D may shift. For example, the approaching “post-shrink” era (beyond the limits of miniaturization for silicon integrated circuits) may demand renewed vigor in basic research to find a successor to silicon ICs.

To suit the needs of those who use the products based on microelectronic devices, R&D efforts in microelectronics are aimed at making circuits that:

- cost less,
- operate at higher speeds (higher frequencies),
- require less power and generate less heat,
- are more reliable and last longer, and
- carry out specific functions.

These goals are prioritized in different ways depending on the end use. For example, low cost is typically the chief concern for chips to be sold in high volume, but high speed may be the dominant requirement in making components for supercomputers, and concerns about power consumption may dominate for ICs intended for use in satellites.

For the microelectronics manufacturer, in the short term, these requirements translate into:[2]

- making ICs with smaller component devices (i.e., smaller transistors, resistors, capacitors, interconnections) and packing these devices closer together on the chip;
- using larger wafers so that more chips can be made on a single wafer;
- using new processes and new equipment in chip fabrication;
- packaging chips in increasingly sophisticated ways;
- designing increasingly complex circuits; and
- designing circuits that are tailored to specific applications.

Scientists and engineers involved in longer term R&D are trying to anticipate technological needs beyond the current generation of products. Their concerns center on topics such as:

- new materials for microelectronics (e.g., gallium arsenide);
- new devices to replace or augment transistors (e.g., quantum-effect devices);
- new equipment to fabricate these materials and devices;
- integrating optical and electronic circuitry; and
- advanced design tools.

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[2] *App. A: Current Microelectronics Technology* provides some general background information on integrated circuit technology, and *App. B: Glossary of Terms gives* definitions for technical terms.

Chapter 3

Current Research and Development Activity

Microelectronics research and development (R&D) activities can be separated into three categories:

1. activities to improve silicon integrated circuits (ICs),
2. efforts for compound semiconductor microelectronics (primarily based on gallium arsenide (GaAs)), and
3. investigations for integrated circuits based on materials other than semiconductors.

Design activities span all three categories. Most of the work described here is aimed at making better digital integrated circuits. Other semiconductor activities, such as optoelectronics and microwave devices, are also included here because they are merging to some degree with IC technology and because all semiconductor R&D shares a common base of physical understanding and process technology.

ADVANCED SILICON INTEGRATED CIRCUITS

Efforts now underway to improve silicon-based microelectronics will be the first type of R&D to have practical applications. These efforts can be grouped in three categories of simultaneous activities:

1. the improvement of the physical circuits and packaging of integrated circuits,
2. the facilitation of the design and fabrication processes, and
3. the design of new types of ICs for specific markets.

Circuits and Packaging

The process of reducing the size of devices in ICs and increasing their packing densities has several parts. Scientists and engineers are developing devices–transistors, resistors, capacitors–that have feature sizes of less than 1 micron. Despite their small size, these devices must be designed to operate correctly and to control the required amount of power. The interconnections required to hook the devices together are also becoming increasingly harder to make. Each connection must shrink in width but still conduct electrical current with virtually no resistance. The interconnections must lie closer together but still be completely isolated from each other. Designers must lay out both the devices and the interconnections in more and more complex patterns. Finally, the package for the completed chip must allow signals to enter and leave the chip at high speed, so that the package itself does not obliterate the speed advantage of the new circuitry.

These steps have been used to scale down silicon ICs over the past 25 years. Every new reduction in feature size has been significantly more difficult to achieve than the last, and progress has been possible only through the introduction of increasingly complex manufacturing technologies and device and circuit designs. Today's R&D workers face the greatest challenges yet.

Few trends, however, can continue forever. The remarkable feature of Moore's law (the annual doubling of the number of components on a chip) is the range over which it extends before meeting unavoidable limits. Two technological factors limit growth. The sizes of the individual devices and the separations between them eventually become so small that the devices cannot function as desired. In some instances, these dimensions are a few dozen atom layers. The problems involved in interconnecting the devices on a chip also become virtually insurmountable. Together, these make a relaxation in the rapid growth of microelectronics technology inevitable. Microelectronics experts do not agree on the details and consequences of this slowdown, but they generally do agree that these limits will be reached during the next 10 to 20 years.

Design and Fabrication Processes

Activities to facilitate the IC design process are focused on design tools, which simplify circuit layout for IC designers. Particularly as the design process has grown more complex to accommodate the millions of devices, computer-aided design (CAD) systems have become virtually indispensable. Currently, there is no single standardized CAD system; rather, there are several different systems built by different groups of designers. As these systems evolve, they will simplify the design process and thereby give a wider range of users great flexibility in creating new chips.

Fabrication technology includes the processes for depositing very thin layers of different metals, insulators, and semiconductor materials on the silicon substrate; changing the impurity content in the semiconductor; etching the layers; and defining small features in the layers through lithography. Current R&D activities are exploring better techniques to carry out each of these tasks. For example, densely packed circuits may require new materials with special properties—high electrical conductivity, chemical stability, particular crystal structure—for interconnections. Also, x-ray, electron-beam, or other lithographic techniques may be needed to replace current photolithography for better definition of ultrasmall features.

Manufacturing technology is a crucial part of these advances because progress in silicon scaling is based on the introduction and improvement of highly sophisticated equipment. Some examples are chemical-vapor-deposition (CVD) and evaporation systems to grow thin films of semiconductor crystals and metals; lithography equipment and plasma etchers to define the ultrasmall features of the IC; and furnaces and ion implanters to introduce the proper impurities to the wafer.

Circuits for Specific Markets

Currently, most ICs fall into a few standard categories: logic chips, memory chips, and microprocessors. However, as the design and manufacturing capabilities of the IC industry grow and become more flexible, a range of specialized integrated circuits will play a more central role. Application-specific ICs (ASICs) are projected to grow from their current 12 to 15 percent of the total IC market to 25 to 30 percent of the 1990 market. ' This category of integrated circuits includes custom chips, which are designed from scratch for the particular application, and chips that can be adapted by the user for the specific need. Further enhancements of the design process will expand users' ability to design their own ICs.

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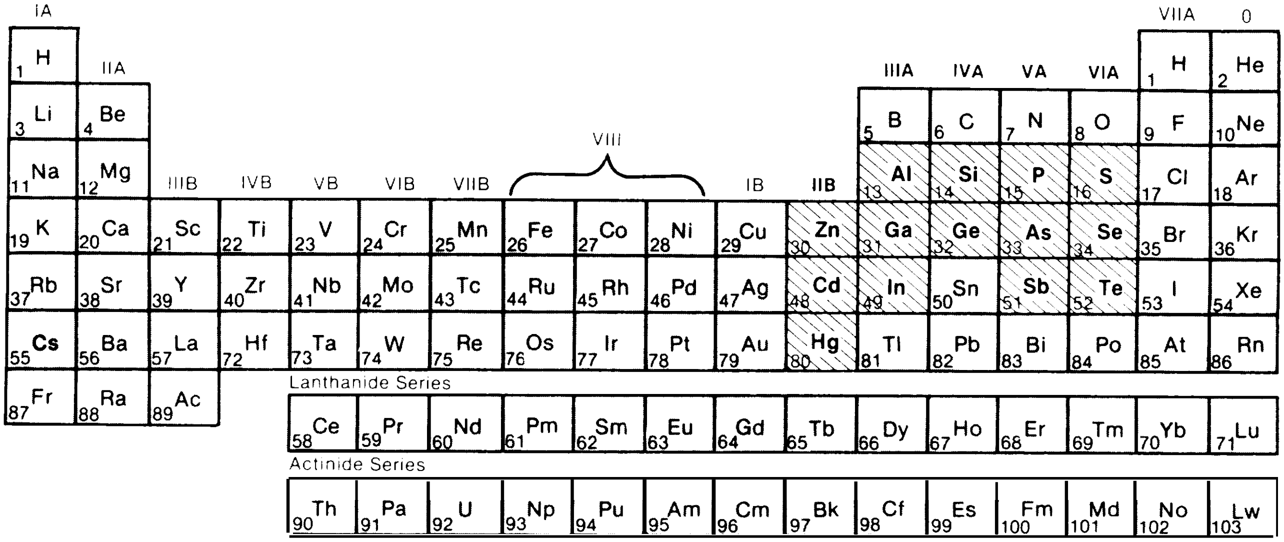
[1] "A Chip Business That Is Still Growing: Innovation Spurs Market for Application-Specific Integrated Circuits, " *Electronics,* July 22, 1985, p. 40.

MICROELECTRONICS BASED ON GALLIUM ARSENIDE AND OTHER COMPOUND SEMICONDUCTORS

From the vantage point of the chemist or physicist, there is a logical progression of semiconductor materials in the periodic table from silicon (a column IV material), to compound semiconductors made from the columns adjacent to silicon (II I-V compounds such as GaAs), to compounds made from the next columns (II-VI compounds such as cadmium telluride). (See figure 1. In this terminology, the Roman numerals refer to the columns on the right side of the periodic table; e.g., "III-V" refers to columns 111A and IVA.) This progression is also useful for classifying the range of R&D activities in semiconductor microelec-

Figure 1 .—Periodic Table of the Elements



IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIII			IB	IIB	IIIA	IVA	VA	VIA	VIIA	0
1 H																1 H	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											**13 Al**	**14 Si**	**15 P**	**16 S**	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	**30 Zn**	**31 Ga**	**32 Ge**	**33 As**	**34 Se**	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	**48 Cd**	**49 In**	50 Sn	**51 Sb**	**52 Te**	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	**80 Hg**	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac															

Lanthanide Series

58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu

Actinide Series

90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lw

NOTE Elements in boldface are those commonly used to make semiconductor materials

SOURCE Off Ice of Technology Assessment

tronics, since the most immediate development efforts focus on silicon, and longer term work usually focuses on compound materials.

GaAs and other 111-Vs are now the basis for a variety of discrete microelectronic devices, as described in appendix A. Current R&D efforts involving these materials focus on.: 1) GaAs digital integrated circuits, 2) advanced optoelectronic devices, and 3) monolithic microwave devices. R&D on design tools, which is critical in silicon technology, is also very important for these alternative technologies.

GaAs Digital Integrated Circuits

Digital integrated circuits based on materials other than silicon continue to receive attention in the research community. GaAs-based integrated circuits are currently the leading contender for next-generation technology. Even so, it is important to note that virtually no experts believe that GaAs ICs will usurp the position of silicon for most applications.

Gallium arsenide has several intrinsic physical properties that distinguish it from silicon. The typical devices made from GaAs operate faster and consume less power than silicon devices. They are also less likely to malfunction in the presence of radiation. However, since a compound semiconductor is intrinsically more complicated than a single-element semiconductor (silicon), GaAs is a much more difficult material to grow, to handle, and to use to fabricate reliable devices.

At present, many barriers impede prospects for making GaAs ICs at production capacity compared with silicon ICs, which are readily produced in quantity. Silicon ICs are currently fabricated on wafers with 5- or 6-inch diameters, while 3-inch wafers are the largest current size for GaAs. Standard silicon wafers have far fewer defects and are less brittle than the best GaAs wafers. Some processing steps for silicon IC technology can be adapted directly for GaAs ICs–portions of the lithographic procedure, wafer handling, clean-room requirements. But the steps involving other materials, such as oxides and other insulators, metals, and polycrystalline semiconductor material, must be developed specifically for GaAs. This requires a more complete understanding of the chemistry and physics of the interfaces between these materials. In addition to all of these fundamental difficulties, GaAs IC technology suffers because experience with it is very limited, relative to silicon. Many of the problems, however, will probably be solved as experience accrues.

The list of organizations supporting (and not supporting) R&D in this area reveals quite clearly the microelectronics community's views on the applicability of GaAs ICs. DOD is the leading Federal supporter of research in this field, because military applications, particularly in space, require the properties GaAs offers: high speed for large-scale signal processing, low power to minimize bulk and energy consumption, and radiation hardness for reliability in the presence of radiation. Major computer and communications companies-e. g., AT&T, IBM, and several Japanese companies —are also investigating GaAs ICs, primarily for use in the parts of their systems that require the highest speed, e.g., computer front ends. Supercomputer companies, most notably Cray, are attempting to make supercomputers based on GaAs ICS. However, the standard merchant chip makers (e.g., Intel, Fairchild Semiconductor, Advanced Micro De vices), which tend to concentrate almost exclusively on short-term development activities, have no onsite efforts in materials other than silicon. Some of these companies support longer term projects, including GaAs work, at universities and through cooperative research organizations. This balance of support indicates two things:

1. GaAs digital ICs are beginning to find niche applications in a variety of areas, and
2. they will probably not make a significant dent in the standard IC components market for several years.

Optoelectronics

As described in appendix A, compound semiconductors and their alloys are currently used to make devices that convert electrical signals to light signals and vice versa. The devices are used for optical communications and sensor applications. R&D activities in optoelectronics fall into three categories:

1. advanced discrete light sources and detectors,
2. integrated optoelectronics, and
3. superlattices and other quantum-effect structures.

The II I-V compound materials used for optoelectronics include GaAs, iridium phosphide (InP), gallium phosphide (GaP), aluminum arsenide (AlAs), iridium antimonide (InSb), and alloys of these materials, such as aluminum gallium arsenide (AIGaAs), iridium gallium arsenide (InGaAs) and iridium gallium arsenide phosphide (InGaAsP). Similarly, important II-VI materials include cadmium telluride (CdTe), mercury telluride (HgTe), and their alloy, mercury cadmium telluride (HgCdTe). These materials are designated as binary, ternary, or quaternary depending on the number of elements found in them. The alloys actually represent a range of materials; for example, half the atoms in HgCdTe must be tellurium, but the other half may be any combination of mercury and cadmium atoms. The properties of the alloy generally lie between the properties of the binary materials that compose it. The particular composition of an alloy is typically chosen to have a certain desired wavelength response. The standard approach to fabricating optoelectronic devices is to grow thin layers of ternary or quaternary alloys on a substrate of a binary material.

Discrete Optoelectronic Devices

The first optoelectronic devices for fiber optic communications were made of GaAs and AlGaAs. The best current devices, however, are based on different compositions of InGaAsP grown on substrates of InP, structures that generate and detect light over a range of wavelengths that includes those of lowest loss (1.55 microns) and lowest dispersion (1.3 microns) in optical fibers. Since these devices are relatively new, the materials and processing problems have not been completely resolved. R&D efforts in this area focus on making devices more reliable and more tolerant of extreme environments, achieving more precise control of the generated light, and developing production processes (with high throughput and yield) for the devices.

The II-VI compounds are used to fabricate long-wavelength infrared sensors because these materials (especially HgCdTe and CdTe) are sensitive to the wavelengths of interest—from around 1 micron to the 10- to 12-micron range. Currently, research on these devices centers on materials properties, which are much more difficult to control in the II-VI compounds than in other semiconductors.

Integrated Optoelectronics

Individual optoelectronic devices can be integrated and fabricated on a single substrate much as standard electronic devices are integrated on a chip to make an IC. An integrated optoelectronic device, typically built on a substrate of InP or GaAs, may be composed of lasers, devices to amplify and modulate the light signals, and light detectors. In addition, the same chip may have purely electronic devices that process electrical signals. Such an integrated chip has all the advantages of a conventional integrated circuit—miniaturization, high speed, low power, fabrication reliability—and also solves the alignment and vibrational-stability requirements for the optical elements it comprises. In addition, it brings optical and electronic devices so close together that signal delays between them are minimized, allowing high speeds to be achieved.

The basic concepts for integrated optoelectronics may be extrapolated even further in the future. Highly advanced crystal growth and processing techniques, currently in their infancy, could also open the door to the possibility of structures that would combine silicon, III-V, and II-VI devices on a single substrate. Such a scheme would allow the flexibility to use the optimal material for each portion of the complete circuit. For example, a circuit on a single chip could be composed of InGaAsP lasers, HgCdTe light detectors, and GaAs and silicon digital logic and memory circuits. Concepts of this sort are still in the speculative stage today.

Superlattices and Other Quantum-Effect Structures

By using sophisticated techniques to deposit materials very precisely, crystal growers can make layers as thin as a few layers of atoms on a semiconductor substrate. Such a layer is approximately one-thousandth of a micron thick-one-billionth of a meter. [2] Structures called superlattices are formed by growing alternating ultrathin layers of two different materials, e.g., GaAs and AlGaAs. Special methods such as molecular-beam epitaxy (MBE) and metal-organic chemical vapor deposition (MOCVD) are necessary to achieve this extreme level of control during crystal growth. These advanced techniques open a completely new set of options for semiconductor materials. Varying the thickness of the layers and their composition can yield a superlattice material with different electronic and optical properties. Quantum mechanical effects dominate the behavior of the electrons in superlattices because the structures have such small dimensions. Thus, the electron transport processes can be dramatically different from the processes in normal material.

Currently, the range of research efforts in this area is very wide, spanning the spectrum from work in designing better systems for growing these precise layers to making devices based on superlattices. The devices include III-V and II-VI photodetectors, lasers, and transistors. The greatest overall contribution of this new breed of materials will probably stem from the fact that they can be tailor-made for a particular application. Already, they are heralded by observers from diverse vantage points as one of the most exciting areas of research today.[3]

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[2] Figure A-3 in app. A shows how small a micron is.

[3] For example, National Academy of Sciences, Committee on Science, Engineering, and Public Policy, *The Outlook for Science and Technology 1985*; and George H. Heilmeier, "Microelectronics: End of the Beginning or Beginning of the End?" International Electron Devices Meeting, December 1984.

Microwave Devices

Analog microwave devices, operating at frequencies from approximately 1 to 60 gigahertz (a gigahertz is 1 billion cycles per second), are commonly made from GaAs to take advantage of the high speed that the material offers. Currently, monolithic microwave integrated circuits (MMICs) are being developed. These circuits combine various microwave devices on a single substrate, typically GaAs. The devices are not packed as densely as silicon devices on a conventional digital IC, but the smallest dimensions are about the same as or smaller than those for silicon ICs—below 1 micron. MMICs will fill the demand for more compact and reliable microwave circuitry for applications in radar, transmission of television and telephone signals, and spectroscopy. A couple of companies have MMICs on the market already, and others plan to market them soon.[4] Most recently, the Department of Defense (DOD) announced that it will launch a major new initiative for MMICs for defense systems. The new program will be analogous to the Very High Speed Integrated Circuit (VHSIC) program, which addresses digital IC technology for DOD.

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[4] "MMICs Save Space, Increase Reliability, and Improve Performance," *Electronics Week,* May 20, 1985, p. 52.

NONSEMICONDUCTOR INTEGRATED CIRCUIT TECHNOLOGIES

Integrated circuits may also be based on materials other than semiconductors. Circuits made of superconducting Josephson junctions have been heavily investigated but are not at present expected to find any large-scale applications in digital microelectronics. Bimolecular electronics is currently only a highly speculative field.

Josephson Junctions

A Josephson junction is an electronic device made by sandwiching a very thin insulator between two superconductors—materials with zero electrical resistance at very low temperatures. Like electronic devices made from semiconductors, Josephson junctions can switch or store electronic signals. Despite drawbacks such as extremely low operating temperatures, they offer several advantages over semiconductor microelectronics. Josephson junctions can switch signals at unparalleled speeds, require very little power, and can be scaled down to extremely small dimensions.

Computer systems based on Josephson-junction technology were intensively researched and developed for over two decades, most notably at IBM. However, IBM halted all but its basic research effort in this area several years ago because packaging, manufacturing, and reliability difficulties meant that the systems could not operate as well as had been originally predicted. Furthermore, while the superconducting technology was struggling to get on its feet, silicon and gallium arsenide technologies kept progressing at a tremendous rate. IBM's cutbacks in this area symbolized a significant change in the microelectronics community's view of IC technology beyond silicon. Currently, although some work on Josephson junctions continues in the United States and in Japan (especially efforts aimed at making high-speed analog circuits), these devices are considered unlikely candidates to pickup where silicon leaves off in digital ICs.

Bimolecular Electronics

In contrast to semiconductor and Josephson junction technologies, the concept of using biological systems to process electrical signals is still in its infancy. Some researchers are turning their attention to biological systems as the extrapolation of the trend to smaller and smaller devices leads to molecular-scale structures.

At present, large-scale bimolecular electronics is a largely speculative area. Some experts envision-a role for biological materials in the fabrication of extremely small structures on semiconductors, and in electronic sensors for medical applications. But the potential for computers based on bimolecular circuitry has not yet been demonstrated.

Chapter 4

Institutional Support for Microelectronics R&D

Because microelectronics is a key commercial and military technology, support for research and development comes from many sources. In the United States, a multitude of private, Federal, academic, and cooperative groups are active in the area. Other nations also support microelectronics R&D; Japan in particular is a growing presence in the field.

FEDERAL SUPPORT

The largest block of Federal funding for microelectronics R&D comes from the Department of Defense (DOD). The National Science Foundation (NSF) funds basic research in areas related to microelectronics. Several other Federal agencies and laboratories have programs to meet their specific needs, among them the National Aeronautics and Space Administration, the National Institutes of Health, the National Bureau of Standards, Lawrence Livermore National Laboratory, and Los Alamos National Laboratory.

Department of Defense

DOD support was crucial to early successes in microelectronics. For example, military requirements for smaller circuits were the primary force behind the development of the first integrated circuits (ICs). While DOD has continued to fund microelectronics R&D extensively and remains the largest source of Federal support for microelectronics R&D, support from private companies has assumed a much larger role, and includes an entire industry that has sprung up in the last few decades. Today, military applications constitute approximately 10 percent of the total sales of microelectronic products. Microelectronics technology is crucial to DOD, and its importance will grow further in the foreseeable future. According to two experts,

> . . . [i]t is safe to say that there is not a single western military system that is not critically dependent for its operation on semiconductor integrated circuits.[1]

Other microelectronic devices, such as sensors, are also becoming increasingly important in military technology.

The defense community, like other users of microelectronics, requires high-speed integrated circuits that consume little power. Since U.S. defense policy has long been based on technological superiority, DOD needs the best possible signal processing and sensor capabilities. Military end users have specific needs as well, including products like ICs that are immune to damage from radiation.

Each of the three services—the Navy, Air Force, and Army—supports activities in microelectronics R&D in DOD laboratories, such as the Naval Research Laboratory, the Air Force Avionics Laboratory at Wright-Patterson, and the Army Electronic Device and Technology Laboratory at Fort Monmouth, and through research agencies. Apart from the services, DOD's Defense Advanced Research Projects Agency (DARPA) is heavily involved in this area. Certain aspects of microelectronics R&D are also covered under a few DOD special programs, such as the Very High Speed Integrated Circuits (VHSIC) pro-

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[1] Alton L. Gilbert and Bruce D. McCombe, "Joint Services Electronics Program: An Historical Perspective, prepared for the U.S. Army Research Office, Electronics Division, April 1985.

gram and the Strategic Defense Initiative (SDI).

Research for the Navy, Air Force, and Army

The Office of Naval Research (ONR), the Air Force Office of Scientific Research (AFOSR), and the Army Research Office (ARO) handle scientific research for their respective branches of the military. All three fund substantial amounts of basic research in microelectronics, with large shares of these funds going to universities. Their areas of interest center on materials and devices. Because the three agencies are organized in different ways, a completely accurate comparison of their levels of support is not possible. However, approximate annual budget figures for microelectronics-related work sponsored by AFOSR, ONR, and ARO are $24 million, $13 million, and $9 million, respectively.[2]

Part of the funding from the three services' research offices goes to support the Joint Services Electronics Program (JSEP). They sponsor the program jointly, with each office contributing approximately one-third of the funding. JSEP is a 38-year-old DOD program that funds electronics research, including microelectronics, at a group of universities. It is designed to provide its 12 member universities with stable, long-term funding for basic research. Total JSEP annual funding has increased since the program's inception to $9.6 million in 1984; approximately 75 percent of this is spent on research on integrated circuits and other microelectronics-related areas.[3]

Defense Advanced Research Projects Agency

The Defense Advanced Research Projects Agency (DARPA), which is separate from the services, supports long-term research for general military applications, including microelectronics R&D. DARPA funds efforts at universities, industrial laboratories, and not-for-profit organizations. One component of DARPA, the Defense Sciences Office (DSO) supports mid- to long-term work on materials, processes, devices, and circuits. Another branch, the Information Processing Techniques Office (IPTO) sponsors activities in very large-scale integration (VLSI) design and architecture and some production automation work.

In fiscal year 1985, DSO had a budget of approximately $34 million for microelectronics, of which $28 million supported basic research and the remainder funded exploratory development. About 40 percent of the total budget went to universities for basic research. DSO sponsors investigations of gallium arsenide (GaAs) and other III-V compounds and their alloys, and work on II-VI compounds, such as mercury telluride and cadmium telluride, and their alloys. Many of these materials have interesting combinations of properties that can be exploited for new applications. DARPA also supports research on the integration of biological materials and semiconductor electronics for ion sensors and other devices.

As of fiscal year 1985, DSO assumed responsibility for the administration of the GaAs IC pilot lines and related activities for SDI. These efforts were transferred to SDI from DARPA at the end of fiscal year 1984. SDI will spend $23 million in this area in 1985, and funding may rise to $40 to $60 million over the next few years, depending on the overall level of support for SDI. Most of these funds are used to support the GaAs IC pilot lines that were originally established and funded by DARPA; additionally, $2 to $3 million from this source goes to universities for basic research activities.[4]

The R&D activities supported by IPTO cover the circuit-design and manufacturing portions of microelectronics technology. Approximately $12 million of the funds that IPTO puts into microelectronics goes to basic research activities in VLSI design and architecture, most conducted at universities. In many cases, this research has later been fun-

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[2] Horst R. Wittmann, Gerald L. Witt, and Kevin J. Malloy, AFOSR; Kenneth L. Davis and Larry R. Cooper, ONR; and Jimmie R. Suttle and Michael A. Stroscio, ARO; interviews and discussion, April 1985 to January 1986.

[3] Gilbert and McCombe, op. cit.

[4] Richard A. Reynolds and Sven A. Roosild, DARPA, interviews and discussion, October 1984 to January 1986.

neled into commercial enterprises. For example, IPTO originally sponsored the "Cosmic Cube" parallel architecture work at the California Institute of Technology; Intel added funding to the Federal money and is now building and marketing a minisupercomputer based on this architecture. In addition, IPTO spends about $6 million per year on exploratory development in automation and fast-turnaround efforts for ICs. These funds cover work on the Metal-Oxide-Semiconductor Implementation System (MOSIS), which gives a large and geographically diffuse community of IC designers, particularly at universities, access to a silicon fabrication facility. With MOSIS, individuals design circuits at their home facilities using a computer-aided design (CAD) system. The design commands are transmitted over a communication network to a manufacturing site, where the IC is fabricated. At present, designers use MOSIS to create new silicon ICs. Activities in progress will also make possible the creation of GaAs-based ICs in a similar systems

Since DARPA is charged with longer term R&D responsibilities, the agency is shifting its focus in microelectronics away from silicon efforts and toward GaAs ICs, while also beginning some activities in more esoteric fields. In some cases, work that DARPA initiated and supported is being picked up by groups more interested in near-term efforts. For example, DOD's VHSIC program and the private Semiconductor Research Corp. (SRC) are taking over the funding of some silicon VLSI programs at Stanford University that were initially sponsored by DARPA.[6]

DOD Special Programs

In addition to the four established agencies, DOD has a variety of special programs that support microelectronics R&D. Examples include the Very High Speed Integrated Circuits program and the new Strategic Defense Initiative. VHSIC is wholly dedicated to silicon IC technology; SDI has microelectronics R&D components as part of a more general mission. DOD also recently announced the start of a new VHSIC-like program to advance the technology of monolithic microwave ICs (MMICs) for defense applications.

The 10-year VHSIC program was established in 1979 to address specific military needs in microelectronics. The three services participate in VHSIC, but the Office of the Undersecretary for Defense Research and Engineering provides overall administration. Honeywell, TRW, IBM, Hughes, Texas Instruments, and Westinghouse are the prime contractors for VHSIC, which is scheduled to finish in 1989.

VHSIC has several goals. The primary technical objective is to establish processes to design and fabricate chips with characteristics necessary for defense needs. The program also intends to ease the adoption of these ICs in military systems. In addition, VHSIC administrators view their program as a mechanism to encourage the commercial microelectronics sector to develop production capabilities suited for the military market. The program is intended to function as a bridge between designers of military systems and the integrated circuit community.

The technological goals of VHSIC are divided into phases. The first phase of the program, now nearing completion, developed pilot lines for the production of ICs with 1.25 micron minimum feature sizes and provided new chips for use in military systems. The second phase will attempt to establish pilot lines to fabricate ICs with 0.5 micron features. At the same time, commercial R&D activities have been and will be developing ICs with similar feature sizes, but the VHSIC chips are designed for specific DOD applications. Although the first phase of activities took longer to complete than originally anticipated, some of the projects have now been carried out successfully.

Because VHSIC's other objectives are longer term and less concrete, their success is harder to assess. Several signs point to

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[5] Paul Losleben, DARPA, interview, August 1985; and presentation on "Silicon as a Medium for New Ideas, IEEE Systems, Man, and Cybernetics Society, Sept. 16, 1985.

[6] Paul Losleben, DARPA, interview, August 1985.

progress; VHSIC chips are used in several military systems in each of the services. And while VHSIC has gotten a mixed reaction from industry over the years, the program has drawn the attention of at least some of the commercial IC vendors to military applications.

As conceived, VHSIC had a budget of approximately $200 million over 10 years. Subsequently, its budget has been expanded to approximately $1 billion to support a range of additional activities. These include efforts to encourage incorporating VHSIC technology in military systems in the three services, the development of a design automation system, and work on yield enhancement.[7]

SDI, started in 1983, is designed to study and perhaps deploy a space-based missile defense. Since microelectronics technology would be central to any such system, one program goal is the development of advanced circuitry for space-based military operations. In addition to the DARPA GaAs work that is now funded through the SD I program element for sensors, SDI Innovative Science and Technology (1ST) office is preparing to support multiple activities in microelectronics research. At present, the programs are being established, and funding levels are being debated. Although final amounts have not been set, it is possible that 1ST will spend several million dollars in this area over the next few years. The funds may comprise dollars from other DOD research pockets (e.g., DARPA, as in the case of the GaAs IC work, or the services' research offices), so they may or may not constitute a net increase in the overall DOD research funding for microelectronics. Currently, contract monitors from other DOD research agencies (primarily ONR) are administering these funds.

National Science Foundation

The National Science Foundation (NSF) is charged with supporting research in a broad range of science and engineering fields. Microelectronics R&D at NSF is funded primarily through the Directorate for Engineering. NSF spends approximately $23 million in areas that include solid-state and microstructure engineering, quantum electronics, electronic materials, electrical and optical communications, and VLSI. These funds support individuals or small groups of researchers.

NSF established the National Research and Resource Facility for Submicron Structures at Cornell University in 1977 and has provided it with about $2 million annually for the last few years. This facility is also supported directly by industrial sponsors and indirectly by other Federal agencies. In addition, NSF has recently established an Engineering Research Center at the University of California at Santa Barbara for Robotic Systems in Microelectronics. NSF plans to give this center up to $14 million over the next 5 years, a sum that the university will probably augment with support solicited from industry. The center will focus on automated systems for IC manufacturing.[8] To some extent, these centers are evidence of a trend at NSF to concentrate its limited resources in a small number of large facilities rather than granting small bundles of money to a large number of investigators.

NSF's style of supporting research differs a great deal from the DOD approach. Defense agencies tend to seek out channels-at universities, in industry, or at DOD laboratories—to accomplish their goals, with a focus on end uses. NSF, by contrast, is not a mission-oriented agency, so it responds to proposals from the research community. NSF's funding for microelectronics and related areas is quite small compared to the total DOD support, but these monies provide some counterbalance to the defense dollars. And while NSF has not played the major role in advancing the technology, it has helped to build a base of qualified scientists and engineers, e.g., by helping new university professors get started with small grants. This gives NSF an important role as a broad basic-research agency.

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[7] Eliot D. Cohen, Navy VHSIC Program Director, interview, July 1985, and additional comments, November 1985.

[8] Evelyn Hu, Associate Director, Center for Robotic Systems, interview, October 1985; and NSF literature on Engineering Research Centers.

PRIVATE SECTOR R&D

Many kinds of private sector organizations are engaged in microelectronics research and development. They may be grouped into two broad categories:

1. captive manufacturers—the parts of large, vertically integrated companies that make microelectronic components for their own products and services (typically computers or telecommunications) or for their defense systems applications (termed "captive" because the primary markets for their microelectronic products are internal); and
2. merchant firms-companies that make integrated circuits and other microelectronic products to sell to the full range of end users.

These categories are not mutually exclusive. Several companies (e.g., Texas Instruments) make microelectronic components for internal use as well as outside sale. However, the division helps to illuminate the nature of R&D in many companies, since the size and goals of the organization are key determinants of its approach to R&D.

Today, the most prominent force changing microelectronics companies (and thus their R&D efforts) is Japanese competition. Merchant vendors are especially vulnerable. This has major implications for industrial R&D. Companies may cut back on R&D investment as part of a general belt-tightening effort. Paradoxically, R&D is increasingly important in the competitive environment. Thus, the companies are beginning to look to the Federal Government for R&D support, either through direct funding for R&D, or through Federal policies that ease the way for private support, such as the tax treatment of R&D expenditures and intellectual property protections.

Captive Manufacturers

Although microelectronics technology is being applied in more and more ways, its primary uses are still concentrated in computers, telecommunications, and military systems. Because these uses dominate the field, most companies with captive microelectronics operations specialize in them.

Since these firms are generally very large and relatively stable, they tend to support a very broad range of activities, from basic research to product development. For example, companies such as IBM and AT&T have thousands of scientists and engineers involved in different aspects of microelectronics R&D.

Telecommunications and computer technologies are beginning to merge because of developments in information technology and also as a result of the recent deregulation of the telecommunications industry. The latter development allowed new entrants into the field and permitted AT&T, formerly excluded, to participate in the computer marketplace. The divestiture of AT&T also split the well-known Bell Telephone Laboratories into two research organizations: AT&T Bell Laboratories and Bell Communications Research (Bellcore), which serves the seven regional Bell operating companies jointly. Although the divestiture of AT&T officially occurred at the beginning of 1984, its long-term effects on research are not yet completely clear. However, there are preliminary indications of trends at the two companies.

Some changes are clearly underway at AT&T Bell Laboratories. R&D activities are, overall, becoming more closely linked with products as a result of the new competitive environment that AT&T faces. Even so, there is ample evidence that at least in areas related to microelectronics the organization will continue to pursue a broad spectrum of basic research as well as development. The new environment has both negative and positive implications for R&D. Scientists and engineers in the research community are concerned that, whether or not AT&T Bell Labs shifts from basic research, it will be less likely to share the fruits of its research with others. On the other hand, the pressure of competition will probably drive AT&T Bell Labs to move research into new products and services faster than it did in predivestiture years.

The prognosis for Bellcore's role as an R&D organization is, if anything, even less certain. Bellcore is a unique laboratory in the United States because it serves seven separate, highly regulated companies. It is not directly linked to any particular manufacturing facility, and so will probably not experience the same shifts in R&D as AT&T Bell Labs. In fact, Bellcore to date exhibits signs of pursuing a vigorous basic research program in microelectronics- and optoelectronics-related areas. But since it is a completely new organization, Bellcore will need several years to establish an identity in R&D.

Other manufacturers of products for industrial and commercial use, such as Xerox and Hewlett-Packard, also contribute heavily to microelectronics R&D. These companies, although significantly smaller than, for example, IBM and AT&T, are still large and diverse enough to support good-sized research efforts. Their specific markets tend to shift the direction of R&D activities, so that each such company pursues a somewhat different research agenda. For example, Xerox's interest in printing technology helped the company to achieve prominence in optoelectronics research.

Of the several captive microelectronics operations that serve the military markets for microelectronics, many carry out DOD-funded and internal R&D. Much of the internal R&D is funded by Independent Research and Development (IR&D) funds which are derived from overhead on defense R&D contracts. The largest players in this category are such companies as Hughes Aircraft, Honeywell, Rockwell, TRW, and McDonnell Douglas. Many other companies that are well known for their commercial efforts are also defense contractors. Typical examples include IBM, AT&T, and Texas Instruments.

Merchant Companies

Merchant companies sell microelectronic products to users who incorporate them in a variety of systems—computers, communications systems, consumer products, control equipment, and defense systems. California's Silicon Valley firms (e.g., Intel and Advanced Micro Devices) are the archetypes of this category. Generally, merchant firms have concentrated on producing standard chips (microprocessors, logic chips, and memories), which have been used in the larger electronic systems. Custom integrated circuits, which are designed for a user's particular needs, have held part of the chip market for many years. As IC design and manufacturing become more flexible, a wider range of application-specific integrated circuits (ASICs), including custom and semicustom chips, is drawing a larger share of the market. During the 1985 slump in IC sales, ASICs constituted the one healthy segment of the market.[9]

Merchant companies, unlike their larger counterparts, tend to limit their R&D to the last stages of development; their central concern is getting the latest design and fabrication technologies into production. Two major factors converge to make longer term R&D efforts improbable in these firms. First, the companies depend on the sale of only one type of product—semiconductor devices—for their survival. They tend to be focused, lean operations, with few discretionary dollars for basic research in an area where even a simple experimental facility costs several million dollars. Second, two hallmarks of the Silicon Valley culture are the ease with which workers move from one company to another, and the frequency with which new companies spring up. Managers in merchant chip firms seldom find that a heavy investment in long-term research pays off in this fluid environment.

However, in the last several years, this community grew concerned that its needs were not being met by universities and other basic research organizations. Manufacturing research, for example, is increasingly crucial to the continued growth of the industry, but it had scant support among basic research organizations.

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[9] "A Chip Business That Is Still Growing: Innovation Spurs Market for Application-Specific Integrated Circuits, " *Electronics,* July 22, 1985, p. 40,

To correct this, many merchant companies today help to support external R&D activities through different channels. For example, several merchant semiconductor firms fund university research through the Semiconductor Research Corp. These companies also cooperate in other R&D ventures. Several merchant companies also independently support research projects at universities. All of these activities center almost exclusively on aspects of silicon technology.

COOPERATIVE R&D

Cooperative research and development activities take different forms: organizations that are jointly funded from several different sources or research facilities that are shared by different groups of workers. These joint efforts represent a relatively new approach to R&D in the United States. In microelectronics, several factors are driving the growing trend toward centralized funding for R&D:

- research in microelectronics requires increasingly expensive facilities, which few participants can afford alone;
- advances in microelectronics depend increasingly on multiple technical disciplines, requiring a number of persons trained in different areas; and
- cooperative research can link academia and-industry, thereby bringing necessary funding to universities and facilitating the process of transferring technology from research to development to production.

Examples of cooperative microelectronics research organizations include the Semiconductor Research Corp. (SRC), the Microelectronics Center of North Carolina (MCNC), and the Microelectronics and Computer Technology Corp. (MCC).[10] Each of these channels funds from a variety of commercial firms to universities and other basic-research organizations. MCNC and MCC also carry out inhouse R&D activities.

In addition, a plethora of initiatives for shared facilities are emerging from Federal funding agencies, ranging from NSF, which recently reorganized to focus resources on a group of Engineering Research Centers, to the Innovative Science and Technology part of the Strategic Defense Initiative Organization, which is actively promoting the establishment of research consortia. While many researchers support this trend, others point out that cooperative research is hardly a panacea for microelectronics R&D. They argue that centralization of resources threatens innovation, and that research done by a large number of individual investigators, who come together in small groups to communicate and collaborate, is the most productive approach.

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[10] The structure and operation of these and other cooperative research organizations are described fully in U.S. Congress, Office of Technology Assessment, *Information* Technology *R&D: Critical Trends and Issues,* ch. 6, OTA-C IT-268 (Washington, DC: U.S. Government Printing Office, February 1985).

UNIVERSITIES AND R&D

Universities serve two main functions in R&D: they perform basic research suited to an academic environment; and they educate and train students who subsequently perform research and development in industrial, governmental, and academic organizations.

Support for research at universities comes from many sources, including military and civilian agencies of the Federal Government, industrial organizations, and combinations of these. Microelectronics research takes many forms in this setting. Universities across the

Nation have individual research programs, typically in such departments as electrical engineering, physics, and chemistry. A handful of universities have large research centers. These include the National Research and Resource Facility for Submicron Structures at Cornell University, Stanford University's Center for Integrated Systems, the Microelectronic and Information Sciences Center at the University of Minnesota, and the Center for Robotic Systems in Microelectronics at the University of California at Santa Barbara.

The university role in preparing students for the R&D community has many facets, some of which have prompted disagreement in the field of microelectronics. Although many observers view the current trend toward large campus engineering facilities as a useful way to train students for the activities they will undertake in industry, some experts are concerned that this trend undermines the well-rounded education that universities ought to provide for their students. Thus, there is an ongoing debate about the best way for universities to fulfill this part of their mission.

FOREIGN ACTIVITIES

Foreign activities in microelectronics R&D are so diverse that a full treatment of the topic is beyond the scope of this paper.[11] However, several prominent features of the Japanese efforts have important implications for U.S. R&D in microelectronics.

Japan is the largest foreign supporter of microelectronics R&D. Although observers have long viewed Japanese development and manufacturing activities as competitive with or superior to 'U.S. efforts in microelectronics, they 'had generally believed that the United States excelled at innovation in basic research. Now, however, Japanese basic research efforts are drawing world-tide attention. In the words of one panelist of the Department of Commerce's Japanese Technology Evaluation (JTECH) Program:

> It is often said that the U.S. invents and Japan copies. . . . [S]uch generalizations are grossly inaccurate and certainly do not favor a genuine understanding of our best competitor. [12]

Japanese companies continue to transfer research concepts to production with great speed. In this activity, they draw extensively from U.S. as well as Japanese basic research results. Another JTECH panelist states,

> They do not seem to have difficulties with the "not-invented-here" syndrome that slows technology advances into the marketplace in the U.S.[13]

The United States has a harder time taking the same advantage of Japanese work. One of the biggest barriers to access to Japanese research by U.S. workers is the language difference.

The structure of the electronics industry in Japan strongly affects R&D. In contrast to the United States, Japan has almost no merchant microelectronics firms. Its large, stable, vertically integrated companies can and do invest more heavily in long-term R&D than U.S. merchant firms. This suggests that the challenge they pose to U.S. competitiveness will remain and quite possibly increase.

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[11] For an extensive discussion of foreign R&D efforts in information technology, see U.S. Congress, Office of Technology Assessment, *Information Technology R&D: Critical Trends and Issues,* ch. 7, OTA-CIT-268 (Washington, DC: U.S. Government Printing Office, February 1985).

[12] Federico Capasso, AT&T Bell Laboratories, quoted in "Japan Reaches Beyond Silicon, " *IEEE Spectrum,* October 1985, p. 52.

[13] Robert S. Bauer, Xerox Palo Alto Research Center, quoted in "Japan Reaches Beyond Silicon, *IEEE Spectrum,* October 1985, p. 51.

Appendix A

Current Microelectronics Technology

This appendix provides general background information about microelectronics technology, the roots of which extend back to the early part of this century. Today, a vast assortment of integrated circuits (ICs) and other miniature electronic devices are on the market. All of these components pass through complex design and fabrication processes before reaching consumers.

Electronics Technology From Vacuum Tubes to Integrated Circuits

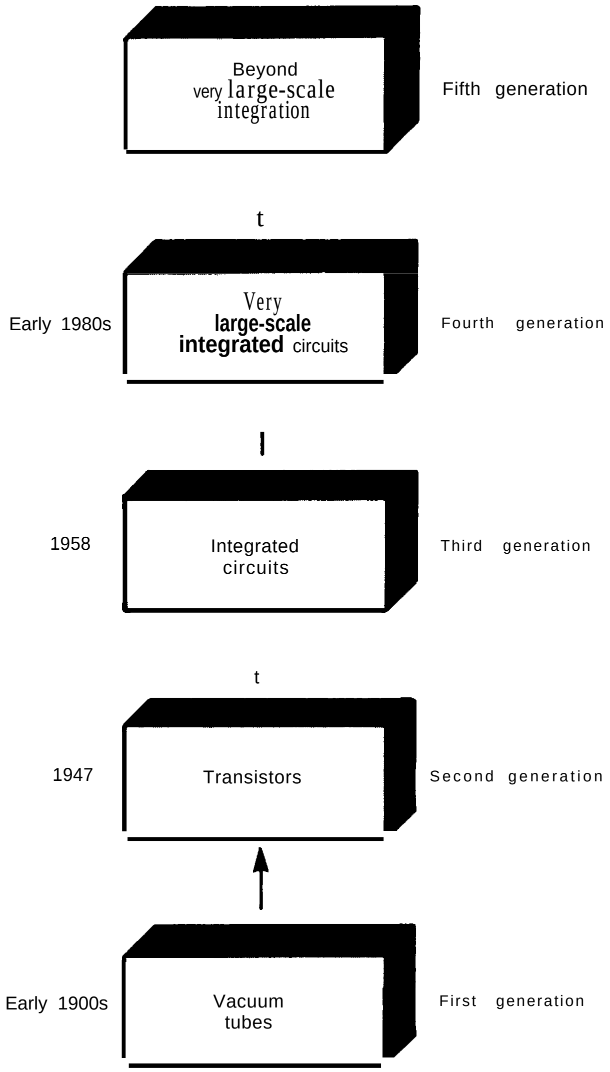
Electronics technology over the last century has advanced in a series of dramatic breakthroughs: the vacuum tube, the transistor, and the integrated circuit. These are often used to designate different generations of technology, as shown in figure A-1.

The history of electronic devices began in the early 1900s with the invention of vacuum tubes, the first devices to reach major use in manipulating and amplifying electrical currents. This technology is limited by several related features. Vacuum tubes require high voltages and, by microelectronics standards, a great deal of power.

The invention of the transistor in 1947 marked the beginning of a new generation in electronics. The inventors fabricated the device from a crystal of semiconductor material to which they added controlled quantities of different impurities. The transistor had three points of electrical contact, or terminals. Like a vacuum tube, it could amplify an electrical signal, but at room temperature, and it required only a small fraction of the power, voltage, and space that tubes demand. The transistor rapidly became the central component in circuits for a variety of applications.

By the late 1950s, transistor-based circuits dominated early computers and military systems. But the drive for increasingly complex circuitry encountered some difficult barriers. Millions of connections were required to turn the hundreds of thousands of components into a functioning circuit—a labor-intensive process with unreliable results. Further complicating things, the total circuit size was growing unmanageable, although the individual components were quite small. The equipment in which electronic devices were used demanded smaller, faster circuits that would consume less power and could be fabricated reliably.

Figure A-1 .—Generations of Electronics Technology



SOURCE Off Ice of Technology Assessment

The next major breakthrough in electronics was the invention of the integrated circuit in 1958. Until this time, all electrical circuits consisted of separate components-transistors, diodes, resistors, capacitors—connected by wires. The inventors of the IC recognized that the wires and other components could also be fabricated from or on the same semiconductor material that was used to make transistors.[1] In this way, they made an entire circuit on a single piece, or chip, of the material. Using this technique, engineers were able to make connections and components by etching the semiconductor and depositing metals and insulators in patterns on the chip. The new process eliminated many of the problems associated with producing highly complex circuits. Because the huge number of connections no longer had to be made by soldering wires together, the IC technique was more reliable and less labor-intensive. The individual components could now be smaller since they would not need to be handled by people. This shrinkage yielded circuits that operated at higher frequencies and consumed less power.

Progress in microelectronics over the last 25 years has been based on further shrinkage of the circuitry etched onto chips. The number of components per chip has, on average, almost doubled every year, Today, up to 1 million transistors and other components are fabricated on a single chip that may have an area of less than 1 square centimeter.

Microelectronic Devices

In this background paper, the term "microelectronics" is used to refer to miniature electronic devices in general. Figure A-2 shows the types of microelectronic devices on the market today. The most numerous and widely used of these are standard ICs made of silicon. Other semiconductor devices, such as optoelectronic and microwave products and discrete devices, are also part of microelectronics technology. Additionally, a few examples exist of miniature devices made from materials other than semiconductors (e.g., magnetic bubble storage devices), but these fall outside the scope of this paper.

Types of Integrated Circuits

Integrated circuits are commonly classified in a variety of ways and referred to with an impressive number of acronyms. They may be categorized by function, by the level of integration (number of components), by the type of transistors used in the circuitry, or by the underlying material (or substrate) on which they are fabricated.

Types of Functions.–Integrated circuits may be either digital or analog (also called linear). In general, a digital circuit switches or stores voltages that represent discrete values. For example, O volts and 5 volts may represent the values O and 1, respectively. An analog circuit, in contrast, amplifies or otherwise modifies voltages of any value within a given range (e.g., any voltage between O and 5 volts). Some integrated circuits are designed to convert signals from analog form to digital form (A-to-D converters) or vice versa (D-to-A converters). Custom chips can combine the various functions. Currently, the majority of ICs are digi-

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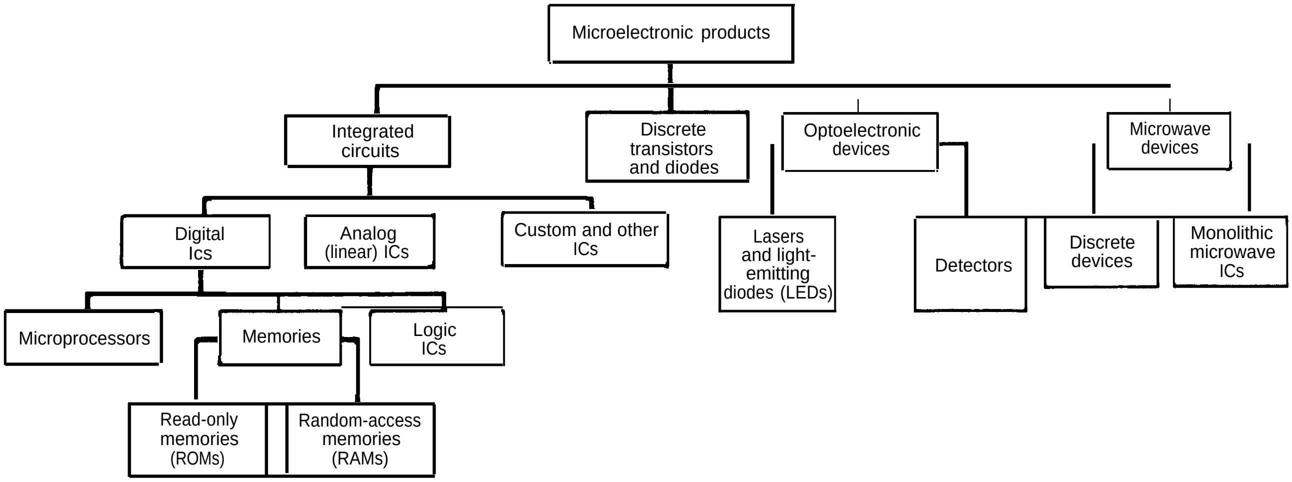
[1] For an account of the invention of the integrated circuit, see T. Il. Reid, 'The Chip," Science 85, February 1985, p. 32, excerpted from T.R. Reid, *The Chip: The Microelectronics Revolution and the Men Who Made It (New* York: Simon & Schuster, 1985).

Figure A-2.—Types of Microelectronic Products



SOURCE Office of Technology Assessment

tal; computers, the major use of ICs, are based on digital integrated circuits.

The major product categories in digital integrated circuits are logic circuits, memories, and microprocessors. All three handle information in the form of electrical signals: logic circuits process the signals, memories store them, and microprocessors combine the two functions.

Logic circuits carry out the operations required to manipulate data in binary digital form. They perform mathematical functions. Logic ICs are typically classified according to the type of transistors used to make them.

Semiconductor memories are microelectronic circuits designed to store information. They fall into two groups: read/write memories and read-only memories (ROMs). Although both groups consist primarily of memories that can be accessed randomly (i.e., any storage location can be accessed in the same amount of time), the term "random-access memory" (RAM) usually refers only to read/write memories. A computer can store a datum in a location within a read/write memory and later retrieve it or store a new datum there. However, the computer can only *retrieve* information that is already stored (by some external means) in a ROM. Thus, a ROM may be used to store unchanging information or instructions that the computer needs regularly, while read/write memories are used to store data as they come into the computer and as they are processed.

Read/write memories may be labeled "static" or "dynamic" depending on the design of the circuits that make up the RAM. Dynamic RAMs (DRAMs) store data in the form of charge on capacitors, and so require that the capacitors be recharged regularly-every few milliseconds. Static RAMs (SRAMs), on the other hand, store data by changing the state of transistors in the storage element, a technique that requires a constant flow of power rather than intermittent recharging to maintain accurate storage. Both static and dynamic read/write memories need a constant supply of power to the circuit as a whole to operate.

Designers can program information into read-only memories in different ways. They may put the information in the physical chip design; this type is known as a mask-programmable ROM. Alternatively, chip manufacturers fabricate ROMs that users can program themselves (programmable ROMs, or PROMs)–a much more versatile product. Some varieties of these PROMS can be erased and reprogrammed using light or electrical signals (erasable PROMS, or EPROMs). EPROMs differ from read/write memories in two ways: they typically cannot be reprogrammed by the computer itself, but they need no power source to retain information.

The capacity of a semiconductor memory is determined by the number of bits that it can store. The maximum capacity available in the early 1970s was 1,024 bits, commonly called a kilobit or kbit. Today, 262,144-bit (256 -kbit) RAMs are on the market, and l,048,676-bit (l-megabit) RAMs are just around the corner. Prices for memories have dropped as dramatically as their capacity has risen: memory costs approximately one-thousandth of a cent per bit today.

Because a microprocessor is a complete computer processing unit on a single IC, it can process data expressed in a series of binary digits or bits (ones or zeroes). The number of bits used in the series determines the precision of the datum's digital representation; precision increases with the number of bits. The original microprocessor, made in 1970 at Intel Corp., was designed to handle four bits. The industry introduced 8- and 16-bit microprocessors by the end of that decade and 32-bit microprocessors within the last few years.

Levels of Integration.—The level of integration of an integrated circuit refers to the number of components packed on the chip. The progress in integration since the invention of the IC is shown in table A-1. Figure A-3 shows how a transistor on an IC compares in size with some other microscopic items.

Types of Transistors. -An integrated circuit may also be classified according to the kind of transis-

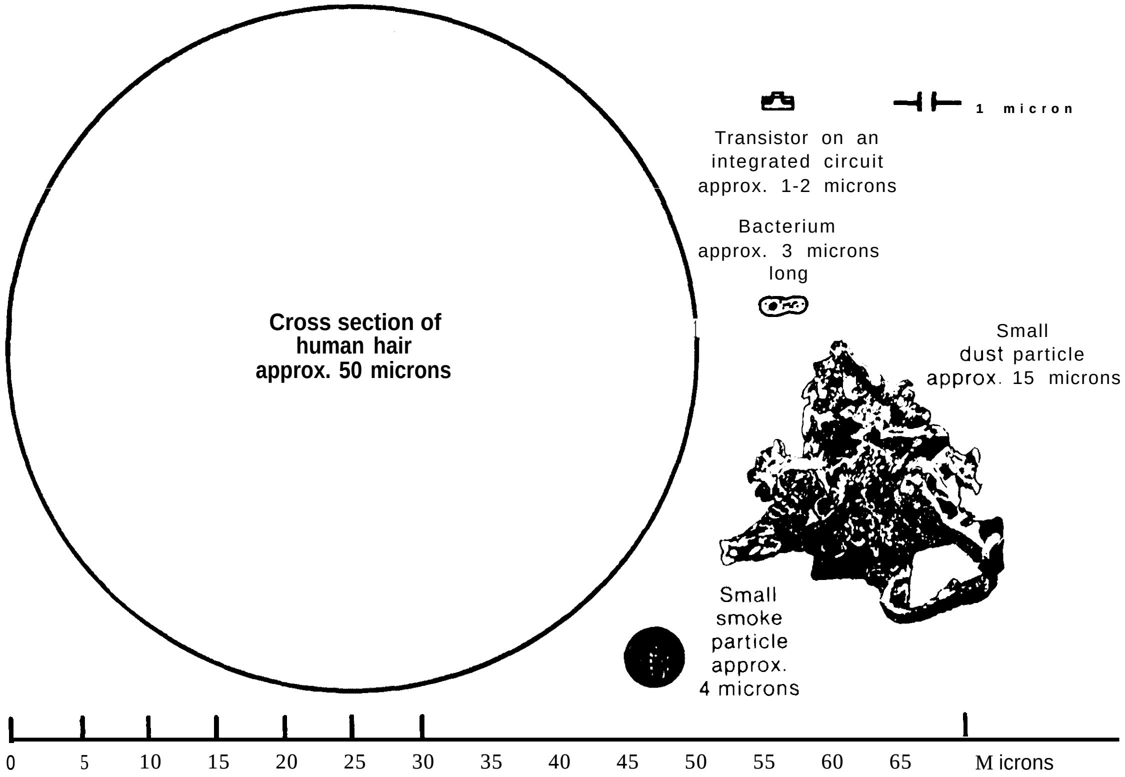
Table A-1 .—Levels of Integration

Level of integration	Design rule (microns)	Number of transistors	Approximate years
Scale-scale integration (SSI)	30-20	2 to 64	1960-65
Medium-scale integration (MSI) ., ...	20-10	64 to 2,000	1965-70
Large-scale integration (LSI)	10-3½	2,000 to 64,000	1970-78
Very large-scale integration (VLSI)	3½ -1 1/4	64,000 to 2 million	1978-86
Ultra large-scale integration (ULSI)	<1 l/4	>2 million	after 1986

NOTE The **numbers** in this table are approximate No standard definition exists for the different integration levels

SOURCE Adapted from James M Early and Bruce E Deal Fairchild Research Center and C Gordon Bell Encore Computer Corp

Figure A-3.—Microscopic Sizes



SOURCE Office of Technology Assessment Adapted from a figure by Jimmie R Suttle Army Research Office

tor used in its design. For silicon ICs, two types of transistors are used: bipolar transistors and metal-oxide-semiconductor field-effect transistors (MOSFETs). These are further subdivided to describe the specific structure of the device and the design of the surrounding circuit. The most common bipolar designations are ECL (emitter-coupled logic) and TTL (transistor-transistor logic); the most common types of MOSFETS are NMOS (n-channel MOS) and CMOS (complementary MOS). (See the discussion of chip fabrication in this appendix for some additional details.)

The primary differences between bipolar and MOS technologies are speed (bipolar transistors are faster); power (MOS circuits require less power); and ease of manufacture (MOS circuits have higher yield). Because the yield determines, in large part, the cost of the chip, bipolar chips are typically more expensive. However, the advantage of higher speed is worth the extra cost and power requirements for bipolar ICs in some applications. For example, most makers of large computers use bipolar ICs for the central components in their machines because they are the only chips capable of the high speeds that are required. On the other hand, personal computer vendors tend to base their products on MOS chips, because cost is generally a bigger concern than speed.

Types of Materials.–Virtually all integrated circuits on the market today are made on substrates of the same material that was the base for the first IC: silicon. The longevity of silicon is due to its physical properties as well as to practical economic considerations. Silicon IC technology is more easily executed than is the technology of compound semiconductors, which have more than one element, because the chemistry of a material made of a single element is innately simpler. Furthermore, once silicon technology was established, economic factors dictated that any replacement be far superior to silicon to be worth the large costs of converting to a new system. And since silicon technology has never stopped progressing-or even slowed significantly-attempts to replace it have been shooting at a moving target. The recent decline of Josephson junction technology (which is based on superconductors) for computers has largely been attributed to this problem.

Despite its great usefulness, however, silicon cannot satisfy all demands of microelectronics. Since transistors made from gallium arsenide (GaAs) can be faster and more impervious to radiation damage than silicon transistors, several companies are trying to introduce GaAs integrated circuits. These ICs are particularly attractive for some military applications (e.g., space-based circuitry), and they may also find standard commercial applications. However, they cannot currently compete with silicon technology for standard functions. For example, a fully operational 1,024-bit GaAs RAM is still in the laboratory phase, while silicon RAMs with over 250 times the capacity have been on the market for some time already, (See ch, 3 for a more detailed description of current R&D activities in this area.)

Other Semiconductor Devices

Semiconductor materials are also used to make a host of individual microelectronic devices, as distinguished from standard silicon integrated circuits. These include discrete transistors and diodes, optoelectronic devices, and microwave devices.

Discrete Transistors and Diodes.—Electronic instruments, including radios, televisions, and control instruments, use not only ICs but also individual transistors and diodes. (Diodes are two-terminal devices that allow current flow in only one direction.) These components are typically made from silicon, The transistors may be bipolar or field-effect transistors.

Optoelectronic Devices. -Semiconductors such as gallium arsenide (GaAs), iridium phosphide (InP), cadmium telluride (CdTe), and mercury telluride (HgTe) are the bases for a range of other microelectronic devices that require properties that silicon lacks—the ability to interact efficiently with light and the ability to operate at extremely high speeds or frequencies.

Optoelectronic devices depend on the first of these properties. Optoelectronics includes light-emitting diodes (LEDs) and lasers, which convert electrical signals to light signals, and photodetectors, which convert light signals into electrical signals. The two major applications for these devices are fiber optic communications and long-wavelength infrared light detection.

Fiber optic or lightwave communications systems use glass fibers to transmit light signals from one point to another; the fibers can replace metal wires that carry electrical signals. Semiconductor lasers or LEDs generate the light signals, and semiconductor photodetectors convert the received light signals back to electrical signals. These devices are most commonly made from layers of GaAs and aluminum gallium arsenide (AIGaAs) on a substrate of GaAs, or, more recently, from layers of iridium gallium arsenide phosphide (InGaAsP) and iridium gallium arsenide (InGaAs) on a substrate of InP. The quaternary materials-different compositions of InGaAsP-can generate and detect the wavelengths of light that travel along the glass fibers with the least distortion (wavelength of 1.3 microns) and fading (wavelength of 1.55 microns).

The primary purpose of long-wavelength infrared (IR) detection is to “see” living or hot objects in the dark. The Department of Defense has spearheaded work on IR sensors, since their potential military uses are many. Typically, the devices are made from alloys of HgTe and CdTe, because these materials can be adjusted to detect the appropriate wavelengths of light (3 to 5 microns and 8 to 14 microns). Special types of silicon diodes can also act as IR sensors in some of these wavelength ranges.

Microwave Devices.-Microwave (high-frequency) devices take advantage of the intrinsic high speed of gallium arsenide. They generate, amplify, switch, and receive microwave signals with frequencies from approximately 1 to 60 gigahertz (1 gigahertz is 1 billion cycles per second). Radar systems and transmission systems for telephone, television, and telegraph signals, which operate at these frequencies, as well as military systems, depend on these microwave devices. This technology is at present progressing to monolithic microwave integrated circuits (MM ICs), in which microwave circuits are fabricated on a single substrate, typically gallium arsenide.

Technologies To Produce Semiconductor Microelectronics

Numerous steps are involved in making any microelectronic device. Integrated circuits are the most complex in this respect. The process can be separated into two parts: circuit design and chip fabrication.

Circuit Design

Once the application for a new integrated circuit is established, the first step in making the chip is the design of the circuit. The use of a wide variety of computer-aided design (CAD) tools has facilitated all parts of the design process for large ICs tremendously. For a digital IC, the overall circuit will typically be a combination of logic functions and storage functions. The designer determines the layout of the subcircuits that carry out each of these functions and the connections between the subcircuits. Also in this initial stage, the chip designer must establish mechanisms for bringing the external signals and power to the various subcircuits. Each subcircuit may itself be composed of smaller, interconnected cells of circuitry. The fundamental units for the designer are the individual components, such as transistors, diodes, resistors, and capacitors, and the connections between them.

Because the process of designing circuits has grown so complex over the years, now involving over 100,000 components on a chip, design software is a major research area which is as important to progress in microelectronics technology as advancements in chip fabrication. As the capabilities of design tools grow, they provide increasingly greater flexibility for different chip architectures, and therefore open the door to using IC technology in completely new ways to fabricate specialized circuits.

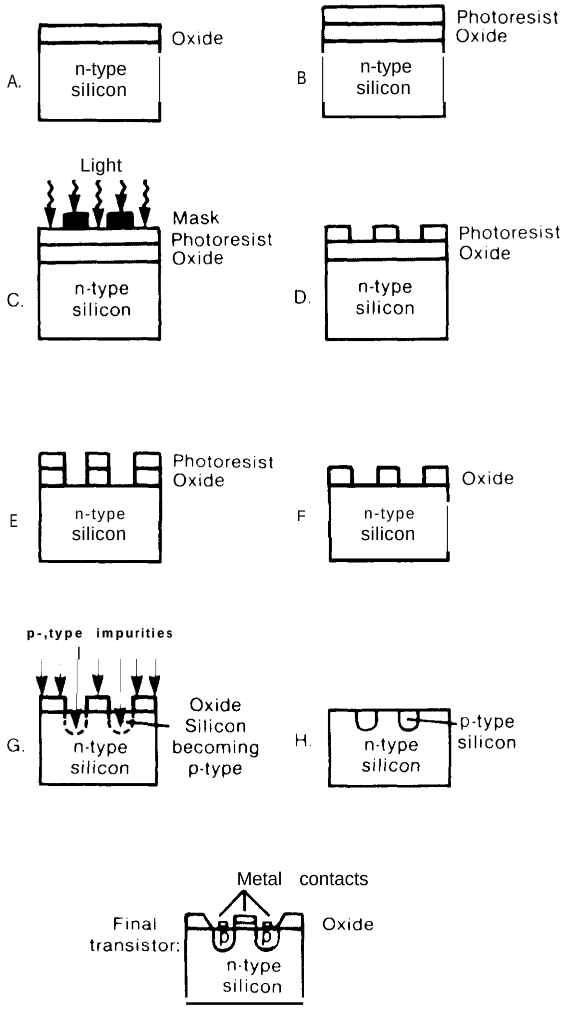
Chip Fabrication

Chip fabrication includes making the circuitry and packaging the completed chip.

The first step of the process is transferring the circuit designers' layout onto the semiconductor chip. The substrate onto which the circuits are transferred is a wafer, or thin slice, of a single crystal of the semiconductor. Currently, a typical wafer is several inches in diameter, so many chips can be made on a single wafer and separated after circuit fabrication. The circuit is created by depositing thin layers of metals, insulators, and perhaps additional semiconductor materials on the wafer; adding n-type impurity atoms (negative charge contributors) or p-type impurity atoms (positive charge contributors) to the semiconductor; and etching away precisely defined portions of the various layers with chemicals or ions.

Illustrating a simplified example of one part of this process, figure A-4 shows the steps in the first phase of the fabrication of a single transistor-an n-channel MOSFET—on a silicon substrate. The objective of this first phase is to add p-type impurity atoms in two small selected regions near the surface of the chip, thereby forming "p-wells." The first six steps of this phase (which constitute lithography) leave a layer of silicon dioxide (SiO_2), with small holes etched in it, on top of the substrate. This layer serves as a stencil for the p-type impurities to which the chip is then exposed: only the portions that are not covered with SiO_2 become p-type.

Figure A-4.– First of Four Mask Processes To Make an N-channel MOSFET



SOURCE Office of Technology Assessment

This process is accomplished as follows. The starting material is a wafer of silicon to which n-type impurities were added during growth. The first step is to grow a thin layer of silicon dioxide on the surface of this substrate, either by exposing the surface to the proper chemicals, or by heating the wafer in a furnace with water vapor (step A in figure A-4). Next, a layer of light-sensitive material called photoresist coats the oxide (step B). The portions of the photoresist that are exposed when the surface is irradiated with light through a glass mask (step C) undergo a chemical change. These parts of the photoresist do not wash away when the chip is rinsed in the chemical developer, but the unexposed portions do (step D). Now, the chip is placed in a bath of chemicals that etch away silicon dioxide, but leave the photoresist and silicon intact (step E). Since the portions of the oxide that are below the photoresist are not etched, this procedure opens windows in the oxide layer. A different chemical bath removes the remaining photoresist without damaging the oxide regions (step F). The chip is now ready for exposure to the p-type impurities, which are driven into the chip either from a piece of source material in a furnace or by accelerating impurity ions into the material (step G). When the number of p-type impurities exceeds the number of n-type impurities that were there originally, the wells will exhibit p-type behavior. Finally, when the p-wells have been formed, the remaining SiO_2 can be chemically removed (step H).

After three more mask cycles, the completed device is composed of regions of semiconductor with p- and n-type impurities; silicon dioxide, which acts as an electrical insulator; and aluminum electrical contacts. In present-day chips, the physical separation between the regions with p-type impurities may be less than 1 micron, and the entire transistor is invisible to the naked eye. Furthermore, the number of impurities must be controlled to within a few parts per billion in some regions of the device.

Fabricating an entire integrated circuit is significantly more complicated because a larger number of much more complex masks are necessary. Chips now also require extremely sophisticated techniques for selective etching of materials, photoresist exposure, and other parts of the process. All of these processing steps must be carried out in an environment completely free of particulate —clean-room facilities. Thus, it is not surprising that the trend in chip fabrication has consistently been towards greater automation of the processes, which reduces the chances of contamination or human error. Today, most machines used in chip fabrication can handle cassettes containing many large wafers of silicon, minimizing the need for humans to handle the delicate circuitry.

When the final lithographic procedures are complete, the large silicon wafer is tested and diced to separate the individual chips. The good chips are then assembled in packages appropriate for their particular applications. Packaging technology is a crucial part of the production of ICs. Proper packaging techniques can shield the chip from physical damage and some forms of radiation damage, For commodity ICs that are sold to a variety of end users, standard packaging systems are necessary to ensure that chips are interchangeable. On the other hand, chips designed and used for high-speed computation require special custom packages that maximize the speed with which signals enter and leave the chip, since standard packaging schemes could obliterate the special speed advantage of the chip by itself.

Appendix B

Glossary of Terms

Chip: A small piece (typically less than 1 square centimeter) of a semiconductor wafer. Also used to refer to a packaged integrated circuit.

Compound semiconductor: “A semiconductor made of a compound of two or more elements instead of a single element like silicon, III-V semiconductors are made from elements in group 111 of the periodic table (such as aluminum, gallium, and iridium) and group V of the periodic table (such as nitrogen, phosphorus, arsenic, and antimony). Binary compounds are made with two elements, ternaries with three elements, and quaternaries with four elements. ”

Custom and semicustom integrated circuits: ICs that can be designed to varying degrees by the end user for a specific application. Full custom ICs are designed and fabricated from scratch: semicustom chips allow the user to modify a chip for the application.

Design rule: Minimum feature size. Current chips typically employ design rules of 1 micron or greater. See table A-1 in app. A.

Diode: A two-terminal electronic device that allows current to flow freely in one direction only.

Gallium arsenide (GaAs): A compound semiconductor with properties necessary for very high-frequency microwave (analog) devices and optoelectronics. There are also several efforts to make high-speed digital ICs based on gallium arsenide.

Integrated circuit (IC): Electronic circuits, including transistors, resistors, capacitors, and their interconnections, fabricated on a single small piece of semiconductor material (chip). Categories of ICs such as LSI and *VLSI* refer to the level of integration, which denotes the number of transistors on a chip. ICs may be digital (logic *chips, memory chips,* or *microprocessors)* or analog. The transistors that ICs are made of may be bipolar transistors, or one of a variety of metal-oxide-semiconductor (MOS) transistors.

Logic chips: ICs that manipulate digital data. See app. A.

LSI: Large-scale integration. See table A-1 in app. A.

Memory chips: Devices for storing information in the form of electronic signals. See app. A.

Microprocessor: A computer central processing unit on a single chip. See app. A.

Micron: One-millionth of a meter. See fig. A-3 in app. A.

Microwave circuit: An analog circuit designed to process high-frequency signals. See app. A and ch. 3.

MMIC: Monolithic microwave integrated circuit. See app. A and ch. 3.

Optoelectronic devices: Devices that convert light signals to electronic signals and vice versa. See app. A and ch. 3.

RAM: Random-access memory. See app. A.

ROM: Read-only memory. See app. A.

Semiconductor: A crystalline material whose electrical conductivity falls between that of a metal and that of an insulator. Semiconductor materials are used to fabricate virtually all microelectronic devices. Silicon is the most common; others include germanium, gallium arsenide (GaAs), indium phosphide (InP), mercury telluride (HgTe), cadmium telluride (CdTe), and alloys of these compound semiconductors. See fig. 1 in ch. 3 for a periodic table of the elements showing common elements used in semiconductors.

Substrate: A piece of material, typically a semiconductor, on which layers of materials are deposited and etched to fabricate a device or a circuit.

Transistor: A three-terminal electronic device that can be used to switch or amplify electronic signals.

VLSI: Very large-scale integration. See table A-1 in app. A.

“Japan Reaches Beyond Silicon,” *IEEE Spectrum,* October 1985, p 46.