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]

[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.

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.

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-

[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. Dl; 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

‘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-

[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.

[9] From the boycott petition, as quoted in "Star Wars Boy-cott 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.