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-

[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 (J SE P). 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 II I-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 SD I 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-

[2] Horst R. Wittmann, Gerald I.. 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

[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.

[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.

[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.

[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.

[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.