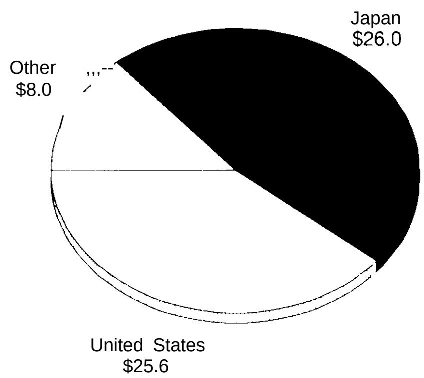
The Semiconductor Industry 3

Over the past three decades, semiconductor manufacturing has become increasingly vital to the U.S. economy. Not only does the U.S. semiconductor industry generate over $25 billion in annual sales and employ over 200,000 workers, but, as an enabling technology for most electronic products, it is essential to the generation of millions of high-wage, high-skill jobs and sales of over $300 billion in such industries as computers, telecommunications, and industrial equipment. Products based on semiconductor technology contribute in turn to productivity gains in many sectors of the U.S. economy.

Nevertheless, the U.S. semiconductor industry faces several challenges that threaten its future competitiveness. International competition has eaten away at U.S. market share, in both the world and domestic markets. Many competitors receive direct support from national governments that have targeted semiconductor technology as a central part of their industrial development plans and have initiated programs to boost the commercialization of semiconductor technology. In addition, the costs of research and development (R&D) and new production facilities are growing exponentially, while sources of patient capital are rapidly eroding. With short product cycles, semiconductor firms are having difficulty supporting the rapid pace of investment and are looking for new sources of financing, often through joint ventures with foreign competitors. Materials and equipment suppliers are also facing financial difficulties.

To date, most U.S. policy in support of semiconductor technology has been limited to ensuring fair trade and protecting

Figure 3-1—Share of World Semiconductor Production by Nation, 1992



SOURCE: Office of Technology Assessment, 1993; based on data from Semiconductor Industry Association, *Annual Databook: Global and U.S. semiconductor Competitive Trends-1978-1991* (San Jose, CA: Semiconductor Industry Association, 1992), p. 12.

national security.[1] Through the Semiconductor Trade Agreement (STA), the U.S. government attempted to open the Japanese market to U.S. producers. Federal funding has concentrated on R&D, the bulk of which has been funded by the U.S. Department of Defense (DoD). Recently, DoD has supported the Semiconductor Manufacturing Technology consortium, SEMATECH. Concern over flagging competitiveness of semiconductor manufacturers in a time of declining defense budgets has, however, induced considerable discussion of means for ensuring the continued success of the U.S. semiconductor industry. It has become increasingly evident that government policy can enhance many areas of technological competitiveness in the industry, and may be necessary in order to preserve its strength. Federal laboratories may have a role to play in working with industry to develop next-generation semiconductor technologies.

A STRATEGIC INDUSTRY

The semiconductor industry holds a strategic position within the U.S. and global economies. In 1992, sales of semiconductor devices topped $60 billion worldwide; U.S. shipments totaled $26 billion (figure 3-1).[2] These figures include sales of all electronic components based on semiconductor technology:[3] integrated circuits (ICs) such as microprocessors and memories; discrete components such as transistors and diodes; and other semiconducting devices such as solar cells and photo diodes. Within the U.S. economy, the most significant of these categories is ICs, which comprised 73 percent of total U.S. semiconductor shipments in 1991, a fraction that has remained fairly constant over the past decade (figure 3-2).[4] Beyond their purely financial effects, integrated circuits, which pack thousands of interconnected circuits onto a single chip, also allow the creation of innovative new electronic products unimaginable with individual, discrete devices. ICs also necessitate the development of sophisticated production machinery and processes, and have large effects on other parts of the U.S. economy.

Contributions to the U.S. Economy

The semiconductor industry contributes disproportionately to job and revenue growth throughout the U.S. economy. Semiconductor manufacturers employed 220,000 workers in the United

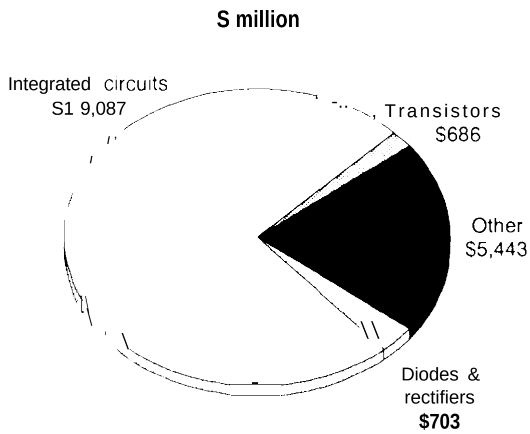
[1] Through NIST, the government has supported the basic metrology that industry needs to manufacture competitive products, but this support has not been as large or as extensive as that for national security.

[2] SEMATECH, 1993 *Annual Report,* p. 6; and Electronic Industries Association 1993 *Edition Electronic Market Data Book* (Washington, DC: Electronic Industries Association% 1993), p. 98.

[3] Semiconductor technology refers to an entire class of materials-and the devices made from them-that have conductivity in between that of an insulator and a true conductor such as metal. Semiconductors derive their conducting characteristics from carefully controlled amounts of impurities (or "dopants"), such as phosphorus, boron, or aluminum, which are inserted into crystals of an otherwise nonconducting material such as silicon or gallium arsenide.

[4] Electronic Industries Association op. cit., footnote 1, p. 98.

Figure 3-2—U.S. Semiconductor Sales by Device Type, 1992 (Estimated)



SOURCE: Office of Technology Assessment, 1993; based on data from Electronic Industries Association, ***1993 Edition Electronic Market Data*** Book(Washington, DC: Electronic Industries Association, 1993), p. 98.

Table 3-l-Comparison of Employment and Earnings in Semiconductors With Other Manufacturing Industries, January 1993

Industry	Employees (thousands) Total	Production	Hourly wages
Semiconductors	220	93 (42%)	$14.23
All manufacturing	17,939	12,185 (68%)	$11.61
Autos	827	635 (78%)	15.52
Aircraft	581	273 (470A)	17.03
Chemicals	1,063	557 (52%)	14.69
Industrial equipment	1,934	1,167 (60°/0)	12.61
Electronic and electrical equipment	1,538	979 (64%)	11.14

SOURCE: U.S. Department of Labor, Bureau of Labor Statistics, ***Employment and Earnings,*** April 1993.

States at the beginning of 1993.[5] Many of these jobs are highly knowledge-intensive, reflecting the large amounts of R&D required to stay competitive in the industry.[6] Only 42 percent of all semiconductor workers were production workers at the beginnin g of 1993, a figure considerably lower than the 68 percent average for all U.S. manufacturing industries. Moreover, many of the production jobs in semiconductors require high levels of skill, involving the operation and maintenance of highly sophisticated production equipment; simple assembly jobs have been either automated or moved off-shore. As a result, hourly wages for production workers in the semiconductor industry averaged $14.23, considerably higher than manufacturing in general and most other electronics sectors (table 3-l).

The semiconductor industry supports a wide-ranging base of suppliers who provide semiconductor manufacturing equipment (SME), control software, gases, chemicals, and silicon substrates. The world market for equipment and materials totaled about $20 million in 1992, with the U.S. market comprising about half of that.[7] On the equipment side, U.S. SME vendors earned $5.5 billion in sales in 1992, 58 percent of which was from U.S. semiconductor manufacturers. SME manufacturers employed over 28,000 workers in 1991.8 U.S.-based materials suppliers earned over $1 billion in revenues in 1992, mostly from sales to U.S. companies.

Even larger effects occur in downstream markets. Semiconductor technology is the key to most modern electronic products: computers, consumer electronics, communications equipment, and industrial equipment. Manufacturers are incorporating semiconductors into products such as automobiles and aircraft as well[9], but

5 U.S. Department of Labor, Bureau of Labor Statistics, “Employment and Earnings, ” April 1993, p. 83.

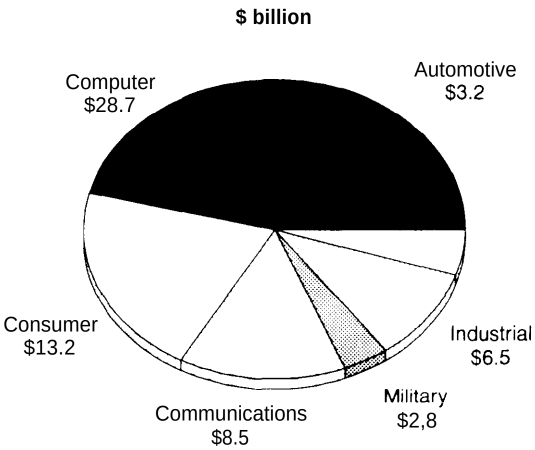
6 Despite the globalization of the industry and the fact that some 50 percent of U.S. semiconductor chips are shipped overseas, American corporations perform about three-quarters of their high value-added wafer fabrication in the United States.

7 National Advisory Committee on Semiconductors, *Attaining Preeminence in Semiconductors* (Washington, DC: National Advisory Committee on Semiconductors, February 1992), p. 9.

8 Personal communication from Peggy Haggerty, Vice President, SEMI/SEMATECH; data from VLSI Research.

9 Approximately 3 to 5 percent of the value of new automobiles is electronics; for commercial and military aircraft, 15 to 30 Percent “the value may be electronics.

Figure 3-3-Worldwide Sales of Semiconductor Devices by Customer, 1992



SOURCE: Dataquest, Inc.

Table 3-2—U.S. Factory Sales and Employment in Electronics by Industry Group, 1992

Sector	Sales (millions)	Employees (thousands)
Communications equipment	$68,097	477
Computers and peripherals	56,360	395
Consumer electronics	9,183	61
Industrial and medical electronics[a]	33,969	279
Semiconductors	27,388	221
Other related products/services[b]	55,875	NA
Electronic components	36,756	374
Total	$287,628	1,807

a Includes control and processing equipment, test and measurement equipment, nuclear electronic equipment, medical electronic equipment, robots, accessories and components, and other electronic systems and equipment.

b Includes estimates of electronic content of the annual sales of industries, such as autos and aircraft, considered partially electronic, as well as computer and software services (but not prepackaged software).

NA = Not applicable.

SOURCE: Electronic Industries Association, 1993 *Edition Electronic Market Data* Book (Washington, DC: Electronic Industries Association, 1993).

approximately 45 percent of the worldwide semiconductor sales in 1992 went for use in computers (figure 3-3). Consumer electronics and communications together purchased another 35 percent of output, while automotive and industrial applications totaled 15 percent of the market. U.S. industries that depend upon semiconductor technology together produced almost $300 billion in manufactured goods and employed over 1.8 million workers in 1992 (table 3-2), making electronics the second largest basic industry in the United States (behind chemicals) and the largest industrial employer.[10]

By 1995, electronics-related industries are expected to comprise 25 percent of all manufacturing.11 U.S. employment in semiconductors and the electronics industry overall is likely to decline marginally through 2005, as is employment in manufacturing generally,[12] due to rising worker productivity, slowing rate of growth of the labor supply as the population ages, and a decline in defense spending. Nevertheless, increases in productive output should continue, especially in the areas of computers and semiconductors, which are projected to grow fastest of all manufacturing areas. Estimates of growth are for 7.6 percent annually in computers and for 5.6 percent annually in semiconductors, both well above the 2.3 percent growth anticipated for all manufacturing industries.[13]

Contributions to National Security

Semiconductor technology is vitally important to national security. Throughout the Cold War, U.S. defense policy was based on the availability of superior technology to overcome the numerical superiority of Warsaw Pact forces. Integrated circuits became integral components of nuclear missiles, precision-guided munitions, early warn-

lo SEMATECH, 1992 *Annual Report,* p. 7.

11 Ibid., p. 7.

12 Max L. Carey and James C. Franklin, ''Industry Output and Job Growth Continues Slow Into Next Century,' *Monthly* Labor *Review, November* 1991, pp. 45-94.

13 Ibid., pp. 58-59.

ing and surveillance systems, aircraft, and communications systems. Concern over the continued development of advanced microelectronics technologies and over foreign dependence on such technologies[14] led the military to invest heavily in semiconductor R&D and to develop procurement regulations governing U.S. content.

While procurement budgets may fall in concert with the declining defense budget, military support of semiconductor R&D is likely to continue at steady or increasing levels. The Advanced Research Projects Agency's (ARPA) funding for electronics manufacturing technology jumped from $98 million in 1991 to over $330 million in 1993. With declining personnel rosters and fewer new starts for major weapons programs, the military will probably rely more on improved semiconductor technology to maintain national security and upgrade existing weapons platforms.

The commercial semiconductor industry is the probable source of many of these components. Commercial semiconductors are in many ways technically superior to their defense counterparts and, due to their larger scales of production, are considerably lower in price.

COMPETITIVE HISTORY OF THE U.S. SEMICONDUCTOR INDUSTRY

Because semiconductor manufacturing has such a strong influence on national economies, many countries--including European nations and Japan—have launched vigorous campaigns to develop indigenous semiconductor industries and gain global market share.[15] Government polices at home and abroad have altered the competitive dynamics of the industry. Though dominating early markets, U.S. semiconductor manufacturers are now increasingly challenged by international competitors.

From the mid-1950s through the early 1980s, the United States was the undisputed leader in virtually all segments of the semiconductor industry. U.S. manufacturers dominated world markets for ICs, manufacturing equipment, and supplies. They invested more than all other nations in new plant and equipment as well as R&D and pioneered new technologies. Throughout the 1980s, however, foreign rivals increasingly challenged U.S. semiconductor manufacturers and, by 1987, had secured approximately 63 percent of the global market for semiconductors. Japanese manufacturers are the primary competitors; at their zenith in 1988, they controlled some 52 percent of the market. Since 1989, U.S. manufacturers have staged a modest resurgence, regaining market share from the Japanese and re-establishing market leadership in 1992 with an estimated 43.8 percent share of the world market (versus 43.1 percent for Japan).[16] These changes reflect a combination of industry initiative and government policy.

■ Early U.S. Dominance

Early American dominance in semiconductors stemmed from the nation's lead in entering the field. Both the transistor and the IC were invented in the United States. Work on solid-state amplifiers began during the 1930s at Bell Laboratories after researchers realized that future switching would need to occur through electronic means, and that future markets would be large enough to justify investment in new technology. These

14 See Institute for Defense Analyses, *Dependence of U.S. Defense Systems on Foreign Technologies* (Washington, DC: Defense Technical Information Service, December 1990).

15 Japan has launched a series of initiatives coordinated by the Ministry of International Trade and Industry (MITI) to stimulate development of semiconductor technology and electronic products. In the 1980s, the European Community initiated the JESSI program to develop semiconductors and the ESPRIT program to promote information technology generally. See Thomas R. Howell, et al., *The Microelectronics Race: The Impact of Government Policy on International Competition* (Boulder, CO: Westview Press, 1988), chapters 3 and 4.

16 Statistics from VLSI Research, Inc., as cited in T. R. Reid, "U.S. Again Leads in Computer Chips," *Washington Post, Nov. 20, 1992,* p. Al.

efforts resulted in the discovery of the transistor by William Shockley, John Bardeen, and Walter H. Brattain in 1947. Jack Kilby at Texas Instruments, Inc. patented the first integrated circuit in 1959 at about the same time that Robert Noyce at Fairchild Camera developed planar processing techniques, upon which current manufacturing is based.

Though commercial interests stimulated work in semiconductor technology, government interest was largely responsible for large-scale production of ICs that led to early domination of the industry by U.S. firms. U.S. industry initially expressed skepticism about ICs. IBM, then the largest single private-sector customer for semiconductor devices, used discrete transistors rather than ICs in its 360-series computer. In 1962, NASA announced plans to use ICs in the Apollo program's guidance computer, and soon thereafter the Air Force stated its intent to use them in the Minuteman II guidance system. These programs allowed U.S. manufacturers to get the economies of scale required to make semiconductors affordable for commercial use and to demonstrate and improve their reliability.[17]

The Japanese Challenge

Japanese companies did not begin producing semiconductors until the 1960s. For many years their products suffered from low yields and high prices. By the mid-1960s, Japanese manufacturers were achieving yields of just 10 percent, compared with 25 percent for their U.S. competitors. Prices were often three times those in the United States. In 1971 Japanese manufacturers sold at more than 20 percent below cost in order to compete with U.S. manufacturers, and as late as 1972, the semiconductor divisions of the major Japanese producers had failed to turn a profit.[18]

In the late 1970s, however, several Japanese companies rose to worldwide prominence in semiconductor manufacturing, due in part to assistance from the Ministry of International Trade and Industry (MITT). Through MITI, the Japanese government provided financial assistance, low-interest loans, accelerated depreciation schedules, and other measures that lowered capital costs and enabled semiconductor manufacturers to continue investing in plant and equipment despite large losses. In addition, MITI organized and helped fund several industry-wide R&D programs, including the successful VLSI Project (1976 to 1979) that targeted dynamic random access memory (DRAM) chips. Over the next several years, Japanese companies achieved higher yields and productivity and lower costs than American firms, particularly in memories, driving many U.S. manufacturers out of the market by the mid-1980s. The U.S. share of the world market for all ICs declined from about 57 percent in 1982 to 39 percent in 1991, reaching its low point of about 37 percent in 1988. Japanese market share rose from 33 percent to 47 percent during the same time (figure 3-4).[19]

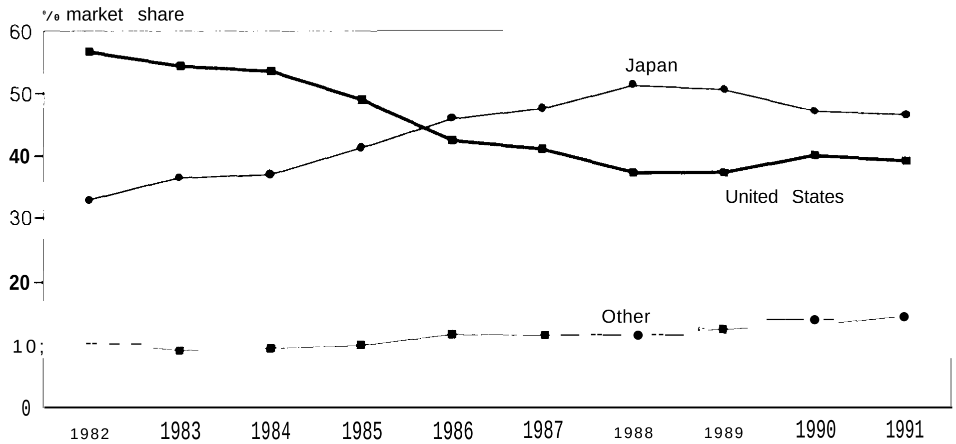
Japanese competition has been most noticeable in markets for commodity chips, such as DRAMs, that are the least dependent on design capabilities and the most dependent on manufacturing capabilities and quality. Between 1978 and 1992, the U.S. share of the global DRAM market declined from about 75 percent to less than 20 percent; Japanese market share grew from 25 percent to 54 percent during the same period (figure 3-5). In more design-intensive, higher value-added market segments, U.S. companies maintained a

17 Arthur J. Alexander, *The Problem of Declining Defense R&D Expenditures*, JEI-14A (Washington, DC: Japan Economic Institute, April 16, 1993), p. 11.

18 U.S. Congress, Office of Technology Assessment, *Competing Economies: America, Europe, and the Pacific Rim*, OTA-ITE-498 (Washington, DC: U.S. Government Printing Office, October 1991), p. 249,

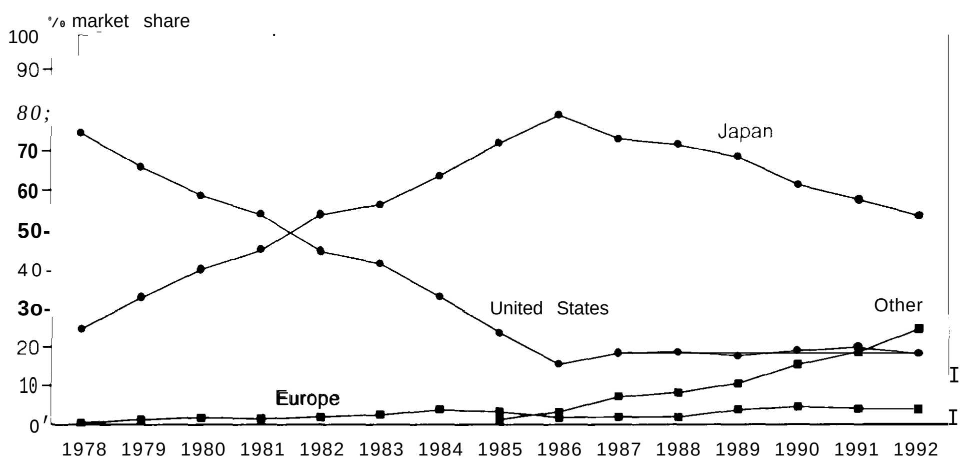
19 Semiconductor Industry Association and Dewey Ballantine, *Creating Advantage: Semiconductors and Government Industrial Policy in the 1990s* (San Jose, CA: Semiconductor Industry Association 1992), p. 9.

Figure 3-4-Semiconductor World Market Shares, 1982-1991



SOURCE: Semiconductor Industry Association, ***Creating Advantage: Semiconductors and Government Industrial Policy in the*** 7990s (San Jose, CA: Semiconductor Industry Association, 1992), p. 9.

Figure 3-5—Worldwide DRAM Market Share, 1978-1992



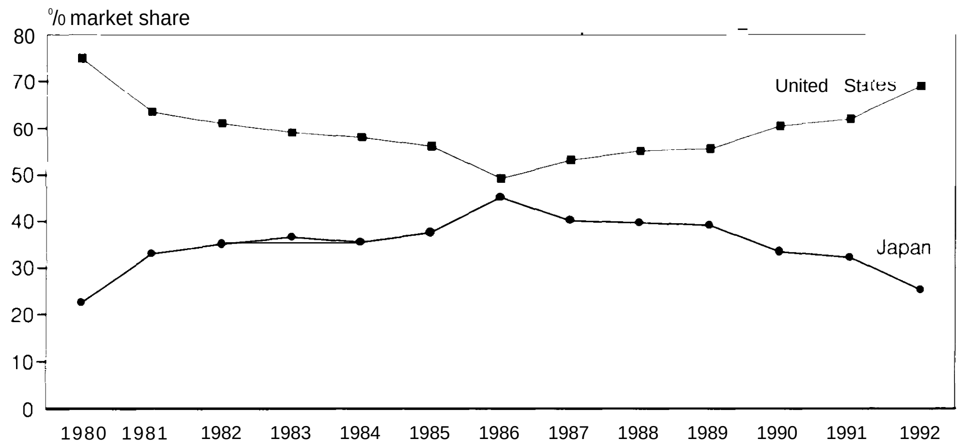
SOURCE: Dataquest, Inc.

dominant position, but the lead was trimmed significantly. U.S. share of the market for micro-components and other types of microcontrollers declined from 75 percent in 1980 to just under 69 percent in 1992 (figure 3-6), while Japanese market share rose from 21 percent to 25 percent. In the market for application-specific integrated circuits (ASICs), which include custom and semi-custom chips, U.S. market share also declined, from 60 percent in 1984 to about 53 percent in 1992, but the United States remained the market leader (figure 3-7).

Reasons for Japanese Success

Japan's success in semiconductors resulted not just from increased funding of R&D. Japan also used a successful mix of financial, technological, and industrial resources to ensure that programs

Figure 3-6-Share of World Market for Microcomponents, 1980-1992



SOURCE: Dataquest, Inc.

Figure 3-7-Share of World Market for ASICs, 1984-1992

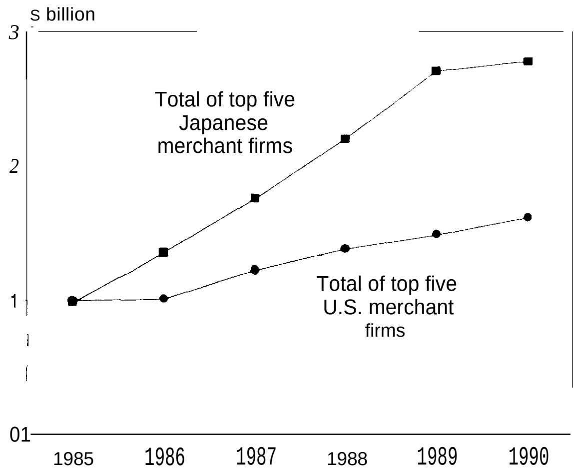
SOURCE: Dataquest, Inc.

were developed rapidly and efficiently, and were pursued over the long term. At the same time, Japanese firms pursued a strategy of expanding market share rather than increasing profitability, often accepting substantial short-term losses in order to establish their market presence and achieve long-term growth. Other differences between Japanese and U.S. trade practices and industry structure (outlined below) also contributed to the Japanese success.

Availability y of Capital

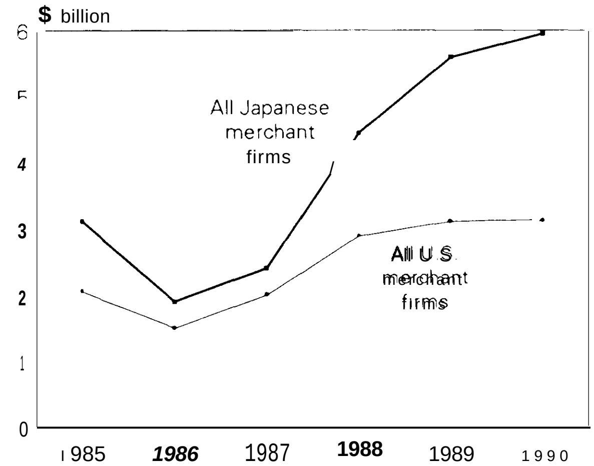
Since 1982, Japanese semiconductor manufacturers outspent their U.S. competitors on R&D and capital goods. In 1988, Japanese capital spending was nearly $2 billion higher than that of the United States; by 1990, Japanese semiconductor manufacturers were spending $6 billion on capital goods versus $3 billion in the United States. R&D spending by the top five Japanese producers also rose from near parity with the United States in 1985 to nearly $1 billion more by

Figure 3-8-Semiconductor R&D Spending



SOURCE: Dataquest, Inc.

Figure 3-9-Semiconductor Capital Spending



SOURCE: Dataquest, Inc.

1990. These differences in expenditures occurred despite the fact that U.S. producers had higher sales that the Japanese until 1986 (figures 3-8 and 3-9).[20]

These spending differences reflect significant differences in government policy and industrial structure in the two nations. By designating microelectronics as a priority industry, the Japanese government increased its attractiveness to prospective lenders and investors; further, the lending policies of the Japan Development Bank, which makes loans to designated priority sectors at MITI's recommendation, have signaled to commercial banks that the government favors microelectronics companies and has thereby mobilized capital for the semiconductor industry .21

Japanese companies also benefited from a lower cost of capital during the 1980s. Although capital costs in Japan have approached those in the United States in recent years, and direct comparisons are difficult to make, Japanese costs appear to have been much lower.[22] Keiretsu banks are a primary source of capital for their affiliated semiconductor producers. During the 1970s, the Japanese semiconductor producers' relationships with the keiretsu banks enabled them to finance aggressive capital expansion through heavy borrowing. While in the 1980s the leading Japanese producers reduced their reliance on debt as a source of capital, their special relationship with the banks remained a critically important asset.[23] Combined with lower interest rates, these relationships helped mitigate the risk associated with large financial outlays.

The structure of the Japanese semiconductor industry also supports greater capital expenditures. Most semiconductor manufacturers in Japan are part of large, vertically and horizontally integrated conglomerates with large assets. Giants like Nippon Electric Corp. (NEC), Hitachi,

20 National Advisory Committee on Semiconductors, *Attaining Preeminence in Semiconductors* (Washington, DC: National Advisory Committee on Semiconductors, February 1992), p. 23.

21 Thomas R. Howell, op. cit., footnote 15, p. 65.

22 National Advisory Committee on Semiconductors, *A Strategic Industry at Risk* (Washington, DC: National Advisory Committee on Semiconductors, November 1989), p. 17. See also Richard P. Matteone, "A Capital Cost Disadvantage for Japan?' Morgan Guarantee Trust, Tokyo, April 1992.

23 Thomas R, Howell, op. cit., footnote 15, p. 65.

and Toshiba are fully integrated; they put their chips into their own products. Integration allows closer cooperation between IC suppliers and systems integrators. More importantly, integration (vertical or horizontal) can make capital available from internal funds outside the IC division, provided other divisions are earning healthy profits. Deep pockets are a particular advantage during market slowdowns, when prices decline. They allow companies to fund long-term R&D and forego immediate returns for long-term growth in market share. This capability allowed Japanese firms to continue investing in R&D and expand capacity during recessions that curtailed U.S. investment. The Japanese then entered the market first for 64-kilobit (64K) and 256K DRAMs, gaining noteworthy competitive advantage.[24]

The U.S. semiconductor industry is dominated by 'merchant' manufacturers who are independently owned and sell their output on the open market. ''Captive" suppliers such as IBM sell the vast majority of their output to their parent company and do not compete on a global basis.[25] The merchant portion of the industry has been the source of considerable innovation within the United States. It has achieved low cost production by standardizing designs for many customers' needs. Companies such as Intel, AMD, and TI are not constrained by the capacity of their own systems divisions, but can expand supply to meet market demand. Owners of captive companies often rely on merchant producers to satisfy peaks in their demand.[26] However, merchant companies have often lacked the financial resources to maintain high levels of investment during general recessions.

Trade Practices

Differences in U.S. and Japanese trade practices have allowed Japanese semiconductor manufacturers to gain a strong foothold in the U.S. market while limiting U.S. participation in the Japanese market. Throughout the early 1980s, in particular, the United States did little to regulate or control the import of semiconductor products from Japan. U.S. electronics companies purchased semiconductors from either U.S. or Japanese suppliers, depending on differences in quality or price. But U.S. semiconductor manufacturers alleged that Japanese semiconductor manufacturers used unfair trading practices to gain market share in the United States. The U.S. International Trade Commission (ITC) found that Japanese manufacturers' dumping of 64K DRAMs in the U.S. and other global markets in 1985 inflicted serious damages to U.S. firms.[27] A similar conclusion was reached in the ITC's investigations of the impact of Japanese dumping on U.S. producers of 256K DRAMs and Erasable Programmable Read-Only Memories (EPROMs). Between 1981 and 1982, and again in 1984 to 1985, Japanese dumping of 64K and 256K memories crippled U.S. competitors. The result was a virtually complete withdrawal by U.S. firms from the DRAM market by the end of 1985. Of 11 U.S. merchant firms that produced 16K DRAMs in 1980, only two remained in the market at the 256K level, and these companies accounted for less than 10 percent of world sales.[28]

In contrast, U.S. firms have encountered two types of barriers preventing the sale of their products in Japan: restrictions on investment, and trade barriers. During the 1960s, foreign semiconductor companies were prohibited from establish-

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[24] Ibid, p. 62.

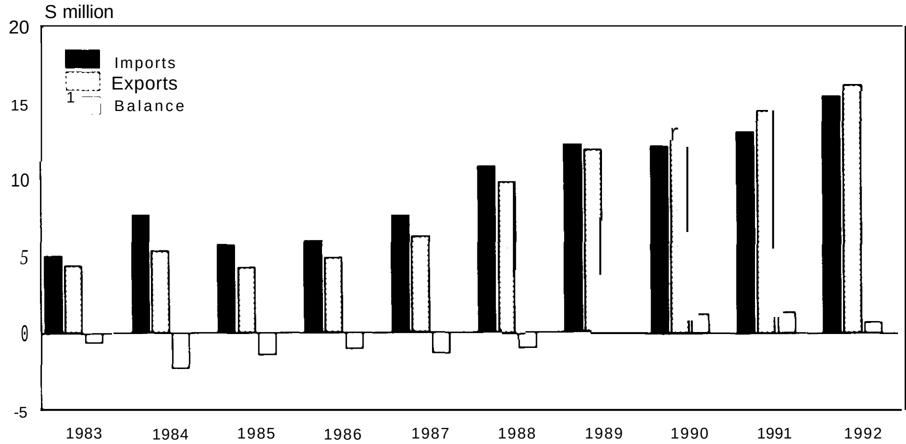
25 IBM recently announced that it will sell ICS on the merchant market. This strategy reflects a corporate restructuring that will disaggregate the company into a larger number of profit centers.

26 National Research Council, Competitive Status *of the US. Electronics Industry (Washington* DC: National Academy Press, 1984), p. 45.

27 U.S. International Trade Commission, *64K Dynamic Random Access Memory Components from Japan,* pp. 19-20.

28 Semiconductor Industry Association, *Creating Advantage,* Op. Cit., p. 105.

Figure 3-10--U.S. Trade in Solid State Devices



SOURCE: Electronic Industries Association, 1993 ***Edition Electronic*** Market ***Data Book*** (Washington, DC: Electronic Industries Association, 1993), p. 114.

Table 3-3-Market Sizes and Market Shares by Geographic Base of Headquarters, 1991

Market	Size ($B)	Market share by nationality of firm (percent) U.S.	Japan	Other
United States	**$15.4**	70	20	**10**
Japan	**20.9**	**12**	**86**	1
Europe	**10.1**	**45**	**15**	40
Rest **of world**	**8.2**	**43**	**34**	**23**
Total	**$54.6**	**39°A**	**47"/.**	**14%**

SOURCE: Office of Technology Assessment, 1993; based on Semiconductor Industry Association, ***Annual*** *Databook:* ***Global and U.S. Semiconductor Competitive Trends, 1978-1991*** (San Jose, CA: Semiconductor Industry Association, 1992), p. 12.

ing subsidiaries in Japan without prior approval of the Japanese government; consent was usually withheld unless companies agreed to form joint ventures with Japanese fins. U.S. companies had difficulty forming ventures with Japan's major electronics companies because MITI favored alliances between Japanese firms over international joint ventures. In addition, MITI required U.S. firms to transfer technology to their partners as part of the deal.[29]

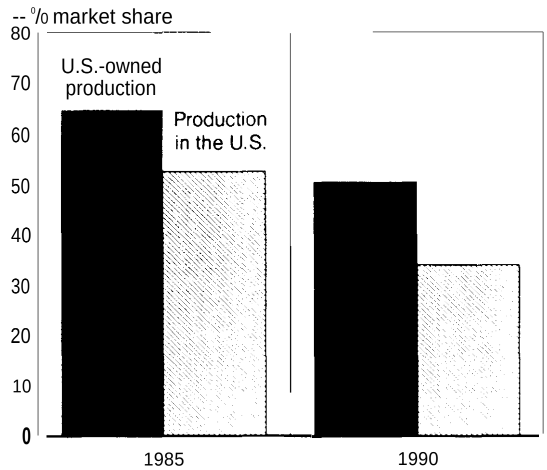
Even with market liberalization between 1974 and 1975, U.S. companies could secure only limited shares of the Japanese market. Japanese semiconductor companies are often divisions of larger conglomerates or of keiretsu that also include producers of electronic goods. These producers tend to purchase components from within their own group, to the detriment of foreign manufacturers. Japanese companies further maintain that U.S. semiconductor firms lack the support and testing facilities of Japanese manufacturers and that U.S. chips have a higher defect rate.[30]

Though dominant in other regional markets, U.S. firms have been unable to penetrate the Japanese semiconductor market and have therefore lost a large share of the total world market (table 3-3). The trade balance has also shifted. Between 1983 and 1987, the U.S. trade deficit in semiconductors increased from $620 million to almost $1.4 billion, due mostly to increasing imports from Japan and stagnant export growth (figure 3-10). Though the United States had run a trade deficit in semiconductors prior to this date,

29 U.S. Congress, Office of Technology Assessment, *Competing Economies: America, Europe, and the pacific Rim,* OP. cit., P. 249.

30 Sheridan Tatsuno, "Japanese Companies Give U.S. Chipmakers A Blunt Opinion of Their Products, " *New Technology Week,* Sept. 23, 1991, p. 6.

Figure 3-11—U.S. World Market Share in Electronics Production



SOURCE: American Electronics Association as cited in National Advisory Committee on Semiconductors, ***Attaining Preeminence in Semiconductors, Third Annual Report to the President and the Congress,*** (Washington, DC: National Advisory Committee on Semiconductors, February 1992), p. 21.

it was based mostly on imports from U.S.-owned assembly facilities overseas. Almost 80 percent of all U.S. semiconductor imports were from offshore facilities in 1976.[31] But starting in 1978, the United States began running a growing deficit with Japan. In 1992, the United States imported $4.4 billion in solid-state components from Japan, but exported only $1.5 billion to Japan.[32]

Shifting Location of Downstream Markets

U.S. inability to penetrate the Japanese semiconductor market has been compounded by the tremendous growth of the Japanese market. U.S. semiconductor manufacturers have witnessed a gradual migration of their customer base to Asia. Between 1985 and 1990, the percentage of the world's electronic systems produced in the United States declined from 52 percent to 35 percent (figure 3-1 1). This trend is the result of both the movement of U.S. electronics production out of the United States in search of lower-wage labor and the development of Asia's domestic electronics industry. Growth in electronics manufacturing in Asia has stimulated local demand for semiconductors. As a result, the Japanese market for semiconductors has grown faster than the U.S. market and is now the largest in the world, totaling $21 billion, or 38 percent of the world market, in 1991 (figure 3-12).

Supplier Industries

The success of the semiconductor industry depends on the success of its suppliers: the semiconductor manufacturing equipment and the materials industries. Throughout the 1980s, U.S. materials and equipment suppliers lost market share to foreign competitors. Between 1985 and 1989, the global market share of U.S. equipment suppliers dropped from about 60 percent to almost 40 percent; Japanese suppliers increased their market share from 35 percent to almost 50 percent. In 1980, nine of the top 10 equipment suppliers in the world were U.S.-owned. By 1990, Japanese companies held five of the 10 top slots, including the top two (table 3-4).

U.S.-based materials suppliers proved no more successful, maintaining only 23 percent of the $9.2 billion world market in 1990. Suppliers in Japan captured 64 percent of the market and held the top four slots in terms of total sales. Moreover, much U.S.-based production is foreign-owned. U.S.-owned firms supplied only 13 percent of the total market for materials, and Japanese-owed firms held a 73 percent share.[33] Of the five largest

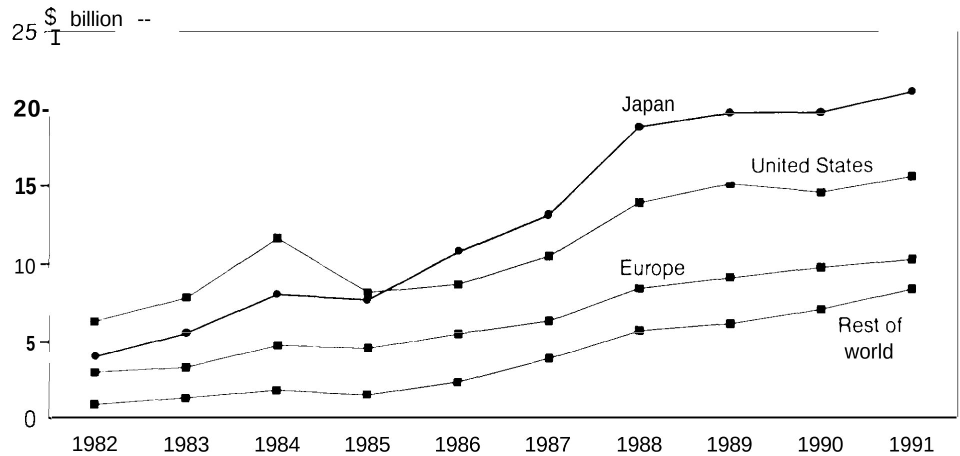
31 U.S. Department of Commerce, International Trade Administration, *U.S. Industrial Outlook, 2978* (Washington DC: U.S. Government Printing Office, 1978), p. 308,

32 Electronic Industries Association op. cit., footnote 2, p. 114.

33 U.S. International Trade Commission, *Global Competitiveness of U.S. Advanced Technology Manufacturing Industries: Semiconductor Manufacturing and Test Equipment,* USITC publication 2434 (Washington DC: U.S. International Trade Commission, September 1991), p. 4-15.

34 These suppliers were Kyocera, Shin-Etsu Handotai, NTK, and Sumitomo (all Japanese), and Huels from Germany.

Figure 3-12-Growth of Regional Semiconductor Markets



SOURCE: Semiconductor Industry Association, ***Annual Databook: Global and U.S. Semiconductor*** Competitive ***Trends-1978-1991*** (San Jose, CA: Semiconductor Industry Association, 1992), p. 13.

Table 3-4-Top 10 Semiconductor Equipment Suppliers in Worldwide Sales

1980 Company (nationality)	Sales ($M)	1990 Company (nationality)	Sales ($M)
Perkin-Elmer (US)	151	Tokyo Electron (J)	706
GCA (US)	116	Nikon (J)	696
Applied Materials (US)	115	Applied Materials (US)	572
Fairchild (US)	105	Advantest (J)	423
Varian (US)	90	Canon (J)	421
Teradyne (US)	83	Hitachi (J)	304
Eaton (US)	79	General Signal (US)	286
General Signal (US)	57	Varian (US)	285
Kulicke and Soffa (US)	47	Teradyne (US)	215
Takeda Riken (J)	46	SVG (US)	204
Total	$888	Total	$4,108

NOTES: US = United States; J = Japan.

SOURCE: SEMATECH, "Strategic Overview," December 1991, p 1-7; data from VLSI Research.

suppliers in 1990, four were Japanese and the fifth was German.[34]

Moreover, the fragmented structure of the U.S. semiconductor industry permeates the supplier industry as well. Throughout the 1980s, U.S. semiconductor manufacturers maintained arms-length relationships *with their* primary suppliers. In contrast, Japanese manufacturers maintained closer linkages to their suppliers. This enabled Japanese manufacturers to gain early access to new production equipment and to influence its design.

The U.S. Response

The loss of U.S. share in the memory market to Japan triggered alarms throughout industry and government in the United States. Though a commodity good with low profit margins, DRAMs were considered the primary technology driver for the entire semiconductor industry throughout the 1980s.[35] The design of DRAMs is fairly straightforward compared with microprocessors and other logic devices, but in order to achieve greater capacity, transistors must be packed more closely together. The design of next-generation DRAMs therefore precipitates advances in lithography and manufacturing capability for achieving higher device densities and smaller linewidths. Logic devices typically lagged behind DRAMs in these areas. In addition, the large volumes characteristic of DRAM production allow for greater evaluation and refinement of production techniques. With large production runs, the effects of process changes upon yield can be more easily determined and the learning that manufacturers gain can be applied to other types of devices manufactured with a similar process. High-volume production also provides manufacturers a way of amortizing the cost of new fabrication facilities (or fabs), which can then be converted for use in manufacturing other devices, such as logic, and for gaining experience with new processes.

Faced with the prospect of continuing its downward slide in market share, the U.S. semiconductor industry took serious measures in the 1980s to regain its international competitiveness. Central to these efforts have been industry collaboration and government cooperation. Government and industry have become partners in reinvigorating an industry that is often considered a strategic national asset. Industry participation has been coordinated primarily by the Semiconductor Industry Association (SIA), an organization that, since its inception in 1977, has gained considerable political influence and has come to represent its member companies effectively. SIA has worked with the federal government to stimulate U.S. research in semiconductor technology, ameliorate trade frictions, and strengthen linkages between semiconductor manufacturers and their suppliers. These efforts have resulted in the formation of the Semiconductor Research Corporation (SRC), SEMATECH, and a series of Semiconductor Trade Agreements (STAs) with Japan.

Semiconductor Research Corporation

SRC was founded in 1982 as an industry-led consortium to coordinate and fund basic university research in technologies of interest to the semiconductor industry. Membership in SRC has grown rapidly to some 70 organizations in 1992. Most members are individual corporations who contribute a freed portion of their total revenues, but other members are government agencies and government/industry consortia, such as SEMATECH and the Microelectronics and Computer Technology Corporation (MCC).[36] With a small staff in Research Triangle Park, North Carolina, SRC manages an external research budget of about $30 million per year. These resources are dedicated to three complementary missions: to support research in universities bearing on long-range industry needs; to increase the flow of graduate students with direct experience related to mainstream interests of the semiconductor industry; and to stimulate interest among university faculty in silicon-related activities and thereby increase the demand for government research support in this area.

[35] Only recently has this notion been challenged. LSI Logic, Inc. has developed a 0.6-micron process for manufacturing ASICs that rivals state-of-the-art DRAM factories, convincing many analysts that DRAM production is not the only way to drive improvements in manufacturing processes.

[36] As of 1992, SRC had 26 full and 33 affiliate members from industry three associate members from Los Alamos National Laboratory, the Microelectronics and Computer Technology Corporation and SEMATECH; and seven members from government, including the National Science Foundation, NIST, the National Security Agency, and other Department of Defense research organizations, who collectively support one full membership for the U.S. government. lb apply for full membership in SRC, companies must manufacture, use, or sell semiconductors. Affiliate and associate members must conduct R&D in support of semiconductor devices within the United States or Canada. Affiliate and associates members do not have representation on the board of directors.

SRC's contribution to university research is evident. Between 1982 and 1992, SRC funded $200 million in university research contracts, supporting hundreds of faculty members and thousands of graduate students. This research generated over 8,000 published reports and 41 patents, with another 38 patents filed.[37] Member firms have access to all these research findings and results. More importantly, SRC finding has helped create interdisciplinary university research programs on silicon-based devices. Though comprising over 90 percent of industry sales, silicon devices received little attention by university researchers a decade ago; the limited semiconductor research at universities was aimed at compound materials (such as gallium arsenide), which have unique electrical properties and are of particular interest to DoD, but have fewer commercial applications.[38] SRC funding now represents about half of all U.S. support for silicon semiconductor research at universities and research institutes.

Transferring research results to industry has not always been easy. Most research projects need further work before they can be commercialized. In addition, finding the appropriate end-user for a specific technology can be difficult. Nevertheless, in 1992, SRC created a new Technology Insertion Program to help move SRC research results into participating companies. These programs are aimed at improving SRC's transfer of technology to industry.

Despite the difficulty with technology transfer, SRC has been highly effective in training personnel for careers in the semiconductor industry and in stimulating personnel exchanges between industry and universities. Member companies are encouraged to send technical personnel to university research centers for extended periods of time to gain exposure to advances in academic research. In addition, members often use their access to students as a means of selecting future employees. Over 1,000 of SRC's graduate students have been hired by industry, bringing with them intimate knowledge of new semiconductor processing techniques.

As a consortium, SRC has also played a key role in helping industry reach consensus on a number of issues. Through its advisory boards, sponsored workshops, and planning documents (like SRC 2001), SRC has developed early industry roadmaps and research agenda for key technologies. These tools have helped SRC raise national interest in issues of importance to the semiconductor industry and attract government attention to industry problems. Furthermore, by maintaining management control of industry's university research funding, SRC has not only advanced a close match between university efforts and industry needs, but has also reduced duplication of research efforts. Though overlap can lead to different and useful results, the high cost of research in the semiconductor industry makes elimination of redundancy a necessity. SRC's success in these areas is widely credited with strengthening the global competitiveness of the U.S. semiconductor industry and improving relations between government, industry, and academia.

SEMATECH

The federal government has also supported SEMATECH, a consortium founded by 14 member companies in 1987 to help U.S. manufacturers recapture world leadership in the semiconductor industry. The group, with facilities and staff at its headquarters in Austin, Texas, proposed to meet this goal by developing within five years a process for manufacturing chips with 0.35-micron feature size on 8-inch wafers. In Decem-

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37 *Semiconductor Research* Corporation, *A Decade of Service to the Semiconductor Industry: 1992 Annual Report* (Research Triangle Park, *NC:* Semiconductor Research Corporation 1992), p. 2.

38 Markets for compound semiconductors are growing, however. Gallium arsenide ICs are now widely used in wireless communications systems; compound semiconductors are used as laser sources in telecommunications systems and compact disc (CD) players.

ber 1987, Congress authorized DoD to provide SEMATECH with five years of funding at a level equal to industry's contribution, expected to be $100 million per year. DoD assigned ARPA responsibility for working with SEMATECH in April 1988.

SEMATECH originally planned to create new production processes in-house for manufacturing next-generation semiconductors, but later decided that its primary goal should be to develop a strong base of semiconductor manufacturing equip ment suppliers. Without strong suppliers, U.S. semiconductor manufacturers could not keep up with their Asian competitors, who have closer contacts with Japanese equipment makers and thus have earlier access to the most advanced Japanese semiconductor manufacturing equipment. At SEMATECH's inception, U.S. semiconductor equipment suppliers were losing market share at the rate of 3.1 percent per year.[39] Semiconductor manufacturers expected to purchase less than 40 percent of their submicron equipment from U.S. suppliers.[40]

SEMATECH established a number of partnerships with U.S. equipment manufacturers to help them develop next-generation production tools. It also brought the semiconductor industry toward consensus as to its future requirements, especially for new semiconductor manufacturing equipment. As a result, equipment manufacturers have been able to produce equipment to one set of industry specifications rather than to diverse company specifications. In addition, SEMATECH has standardized methodologies for evaluating candidate manufacturing technologies, both analytically and experimentally. Perhaps most important, SEMATECH's Partnership for Total Quality program has improved communications between semiconductor manufacturers and their suppliers. While some suppliers had previously maintained close relationships with preferred customers, SEMATECH replaced and repaired those that had been severed and created a much broader set of ties. In this way, information that is not easily quantified can be exchanged directly between users and suppliers of manufacturing equipment.

While critics claim that SEMATECH has benefited only its member companies, others credit the consortium with contributing to the recent improvement in the health of the entire semiconductor equipment industry. Since 1990, equipment manufacturers have reversed their declining market share and currently command 53 percent of the world market, versus 38 percent for Japan.[41] U.S. semiconductor manufacturers now purchase over 70 percent of their equipment domestically. Motorola's new wafer fabrication facility in Austin, Texas, which was originally planned to include 75 percent foreign tools, now has an 80 percent U.S. tool set.[42] Production yields of U.S. semiconductor manufacturers, which were 60 percent versus Japan's 79 percent in 1987, have improved to 84 percent versus 93 percent in Japan.[43] U.S. equipment manufacturers have also increased their market share in Japan, commanding almost 20 percent of the Japanese equipment market in 1992, up from 15 percent in 1990.[44]

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39 Peter Burrows, "Bill Spencer Struggles to Reform SEMATECH," *Electronic Business,* May 18, 1992, p. 58.

40 SEMATECH, *1991 Annual Report,* p. 2.

41 Data from VLSI Research Inc. as cited by Peggy Haggerty, Vice President, Public Policy and Administration, SEMI/SEMATECH, personal communication, July 20, 1993.

42 SEMATECH, 1991 *Annual Report,* p. 18

43 Us. General Accounting Office, "Federal Research: SEMATECH's Technological Progress and Proposed R&D Program," GAO/RCED-92-223BR, July 1992, p. 10.

44 Data from VLSI Research Inc. as cited by Peggy Haggerty, Vice President, Public Policy and Administration, SEMI/SEMATECH, personal communication% July 20, 1993.

Bilateral Trade Agreements

Other than its participation in SRC and SEMATECH, much of which was justified on the basis of national security, federal attempts to boost the competitiveness of the civilian semiconductor industry have been limited almost exclusively to trade considerations. Government polices have been designed to level the playing field by reducing foreign trade barriers and curbing unfair trade practices-specially dumping—that have injured U.S. semiconductor manufacturers. Trade frictions have been characteristic of the semiconductor industry since the early 1980s, when U.S. manufacturers began complaining of difficulties entering the Japanese market and accusing Japanese firms of dumping products in the United States.

The federal government frost attempted to redress these grievances through the negotiation of a bilateral agreement with Japan in 1983, after imports of low-cost 16K and 64K DRAMs from Japan inflicted heavy losses on U.S. manufacturers. While the agreement contained several recommendations to promote U.S. access to the Japanese market and halt dumping, it lacked proper enforcement and by 1985 was defunct, as U.S. market share in Japan plummeted and Japanese companies began dumping 256K DRAMs and EPROMs in the United States.[45]

A second attempt was made after U.S. manufacturers and the U.S. Department of Commerce filed antidumping suits against Japanese firms in 1985, and the SIA filed a petition for retribution against manufacturers who were eventually found guilty of dumping. Through the Semiconductor Trade Agreement of 1986, the United States attempted to sway Japanese producers to sell at cost-based prices and to ensure U.S. manufacturers enhanced access to Japanese markets. A separate side letter to the STA sought commitments by Japan to encourage its semiconductor manufacturers to increase purchases of U. S.-produced semiconductors, with the goal of increasing the foreign share of the Japanese market to at least 20 percent by the end of 1991.[46] Nevertheless, few steps were taken to implement this requirement, and in April 1987 President Reagan announced formal sanctions against Japanese electronics producers. This action, coupled with prospects that Japan might be labeled a priority country under the Super 301 provisions of the Omnibus Competitiveness Act of 1988 and be subject to retaliatory actions by the United States, induced significant changes in Japan's attitude toward the STA. Efforts were soon undertaken to boost foreign sales, including the formulation of market access plans and specific company promises of increased purchases.

The 20 percent target was not reached by 1991, but given signs of improvement, the SIA and the Computer Systems Policy Project lobbied the U.S. government to negotiate anew semiconductor agreement with Japan. Under this accord, Japan agreed to reach the 20 percent mark by the fourth quarter of 1992. By the fourth quarter of 1992, U.S. companies had achieved 20.2 percent, though market share declined the following quarter. Despite efforts by the Clinton administration to get further firm, numerical commitments of market share, many U.S. companies thought such measures unnecessary because they had already become an integral part of Japanese supply networks.

FUTURE CHALLENGES TO THE U.S. SEMICONDUCTOR INDUSTRY

While the efforts of the U.S. government and industry have been somewhat successful in enhancing the competitiveness of U.S. semiconductor industry, additional efforts will undoubtedly

[45] Thomas Howell, op. cit., footnote 15, p. 102.

[46] According to the SIA, the Japanese government originally denied the existence of the side letter and later argued that while committing them to encouraging Japanese companies to increase foreign purchases, it did not commit them to impose numerical procurement quotas on companies.

be necessary. U.S. manufacturers may have regained market leadership in semiconductors and equipment, but Japanese competitors will likely reassert themselves in the near future. Much of the recent slowdown in Japanese semiconductor production is the result of a serious recession that has reduced local demand for semiconductor products. A resurgence of demand could boost production and Japanese market share once again.

U.S. and Japanese semiconductor manufacturers will be faced with a number of additional challenges over the next decade. Industry will need to surmount many technological obstacles in both semiconductor design and manufacture in order to meet future requirements for more complex, sophisticated integrated circuits. At the same time, the industry will have to face increasing costs for R&D and production that could threaten the ability of individual manufacturers to meet their goals.

Technology

Future integrated circuits will offer considerable advantages over existing ICs. Although the specific path of technological development cannot be accurately predicted more than a few years into the future, realistic predictions can be made on the basis of historical trends in IC capability. Since 1959, the number of components per circuit in the most advanced integrated circuits has doubled every year, following a trend line referred to as Moore's Law.[47] This trend reflects two underlying processes: continued reductions in the size of individual devices (e.g., transistors) on each chip-which thereby allow more devices to be packed into each square centimeter of chip-and the simultaneous increases in the size of each die (or chip) .48

As of 1992, state-of-the-art manufacturers could produce 4M DRAMs containing over 300,000 gates per chip on 132-mm^2 chips using 0.5-micron feature sizes. In order to stay on the Moore's Law curves, by the year 2007 they will have to produce 16-gigabit (G) DRAMs containing over 20 million gates on 1,000 mm^2 chips with O.10-micron feature sizes.[49] Future ICs will have greater power demands and will be able to operate on just 1.5 volts of electricity versus the 3.3 to 5 volts required of current portable and desktop systems. Maximum operating speeds will rise from 120 megahertz (MHz) to 1,000 MHz, allowing faster computation. Other criteria will also improve (table 3-5).

Achieving these specifications in the timeframe indicated will require industry to overcome numerous technical hurdles. A recent workshop sponsored by the SIA and attended by representatives of the semiconductor industry, its suppliers, government, and the national labs, analyzed the technological advances necessary to achieve these goals, in keeping with the Moore's Laws projections. The results of this workshop represent a consensus view on industry needs and requirements for the next 15 years. The group identified 11 major areas in which technical progress will be critical (table 3-6). While each area presents a number of difficulties, lithography may prove the most critical (box 3-A). Workshop participants also identified eight cross-cutting competencies that pervade these 11 technology areas. Advances in these specific competencies, outlined below, will allow further progress in the technology areas.

47 Moore's Law is named after Gordon E. Moore who first noted the trend in 1964 and predicted it would continue. Robert N. Noyce, "Microelectronics," *Scientific American*, September 1977.

48 U.S. Congress, Office of Technology Assessment, *Miniaturization Technologies*, OTA-TCT-514 (Washington, DC: U.S. Government Printing Office, November 1991), p. 13.

49 Semiconductor Industry Association, *Semiconductor Technology: Workshop Working Group Reports*, (San Jose, CA: Semiconductor Industry Association, 1993), p. 3.

Table 3-5—Overall Roadmap Technology Characteristics

Characteristic	1992	1995	1998	2001	2004	2007
Feature size (microns)	0.50	0.35	0.25	0,18	0,12	0.10
Gates per chip (millions)	0.3	0.8	2.0	5.0	10.0	20.0
Bits per chip						
DRAM	16M	64M	256M	1G	4G	16G
SRAM	4M	16M	64M	256M	1G	4G
Wafer processing cost ($/cm²)	$4.00	3.90	3.80	3.70	3.60	3.50
Chip size (mm²)						
logic	250	400	600	800	1,000	1,250
memory	132	200	320	500	700	1,000
Wafer diameter (mm)	200	200	200-400	200-400	200-400	200-400
Defect density (defects/cm²)	0.10	0.05	0.03	0.01	0.004	0.002
Levels of interconnect (for logic)	3	4-5	5	5-6	6	6-7
Maximum power (watts/die)						
high performance	10	15	30	40	40-120	40-200
portable	3	4	4	4	4	4
Power supply voltage						
desktop	5	3.3	2.2	2.2	1.5	1.5
portable	3.3	2.2	2.2	1.5	1.5	1.5
Number of 1/0's	500	750	1,500	2,000	3,500	5,000
Processing speed (MHz)						
off chip	60	100	175	250	350	500
on chip	120	200	350	500	700	1,000

NOTES: DRAM . Dynamic Random Access Memory; SRAM - Static Random Access Memory; I/O - input/output.

SOURCE: Semiconductor Industry Association, ***Semiconductor Technology Workshop Reports*** (San Jose, CA: Semiconductor Industry Association, 1993), p. 3.

Materials

There is a critical need for a wide range of high-quality materials for the IC industry, but, to date, industry has undertaken little coordinated materials research. Materials needs include improvements in all feedstock materials, including silicon wafers; wet and dry chemicals used for etching and cleaning; construction materials for equipment and plant; consumables such as resists, masks, ceramics, glasses, metal sputtering targets; packaging materials; and advanced substrate materials (insulators such as glass) on which groups of ICs can be produced and interconnected. Specific needs for substrate materials include dielectrics that are effective insulators at thicknesses of just 50 angstroms; materials for storage cells and capacitors; materials that can be integrated with highly conductive metals for interconnects; and materials for encapsulating and protecting bare chips.

New materials can Provide a competitive advantage for fabrication equipment. Of particular importance may be surface-treated materials for use in construction of etch chambers and other corrosive environments and special materials such as those used in construction of electrostatic chucks.

Metrology

Advances in the ability to measure the results of processing operations are essential to maintain the close production tolerance needed by future

Table 3-6-Technical Areas Identified in SIA Roadmaps

Technical area	Required advances
Chip design and test	Enhanced computer-aided design tools to help engineers design ICs with more devices and complicated interconnections.
Lithography	Reductions in the linewidth and overlay capabilities to allow smaller devices to be drawn on a semiconductor (processes other than photolithography such as x-rays, electron beams, or ion beams may be needed); compatible mask and resist technologies.
Materials and bulk processes	Improvement in processes used for creating oxides and depositing films on the semiconductor wafer; advances in temperature control, mass flow control, materials purity, and modeling of bulk processes.
Manufacturing systems	More robust systems to handle increased volume of data used in lot scheduling and planning, wafer tracking, work-in-process control, failure analysis support, cost accounting, purchasing, and capacity planning; new software tools for managing flexibility in the factory configuration, including process equipment, product mix, and manufacturing technology,
Process/device/structure CAD	New computer-aided design tools to model new processes, circuits, factory equipment, and manufacturing systems; 3-D models to characterize processes such as ion implantation and diffusion. Use of such models will help limit the amount of experimentation needed to bring new processes on-line,
Equipment modeling and design	Advances in models of manufacturing tools for lithography, plasma etching, thermal processing, and epitaxy to allow design of new tools that can reduce base equipment costs, reduce time-to-market through integrated design tools, and improve predictability of performance.
Device/process integration	Progress along the Moore's Law curves will require continued attention to troth front-end (design) and back-end (assembly and test) issues. Advances in process integration will ensure the compatibility of progress in these two areas.
Interconnect	Advances in dielectric and metal film formation and etch processes to allow multiple layers and more complex patterns of interconnection, and therefore higher operating speeds and chip densities.
Environmental safety and health	Means to limit the use of chemicals and processes that are harmful to human health and the environment, or to reduce the risk associated with their use.
Packaging	Advances in the packages that house ICs to ensure the integrity of the electrical signals and the power provided to the chip.
Manufacturing facilities	Advances in wafer handling systems and raw materials systems (for wafers and gases); development of smaller "micro-fabs" that can efficiently produce small batches of wafers, yet be scaled up for mass production, and the manufacturing tools required to support them.

SOURCE: Office of Technology Assessment, 1993; based on Semiconductor Industry Association, *Semiconductor Technology* Workshop *Reports* (San Jose, CA: Semiconductor Industry Association, 1993).

Box 3-A–Advances in Lithography

Central to future advances in semiconductor manufacturing will be advances in lithography. Lithography is the primary technology driver for boosting the performance of integrated circuits. Lithography includes exposure, resist processing, coating and developing, masks, and their associated processing. It is also the dominant cost factor in semiconductor fabrication, accounting for 35 percent of the processed wafer cost,

Table 3-7—Requirements for Lithography Systems

	1992	1995	1998	2001	2004	2007
Leading Edge DRAM size (bits)	16M	64M	256M	1G	4G	16G
Resolution (nm)	500	350	250	180	120	NA
Overlay (nm)	150	100-200	75-95	50-70	35-50	NA

NOTES: M = megabits; G = gigabits; nm = nanometers; NA = not available.

SOURCE: Semiconductor Industry Association, *Semiconductor Technology Workshop* Reports (San Jose, CA: Semiconductor Industry Association, 1993), p. 37.

In order to further reduce the size of the individual devices on an integrated circuit, continued improvement will be needed in both the resolution and overlay capabilities of lithography systems (table 3-7). Resolution determines the width of the smallest line that can be etched into the silicon wafer. Overlay capability refers to the ability of the system to properly align subsequent layers of integrated circuit on top of those below it. Both depend strongly on the wavelength of light used in the *exposure* (shorter wavelengths allow higher resolution for narrower linewidths) and on the method used to project the light onto the wafer. In projection lithography systems, a mask about five times the size of the desired pattern is placed between the light source and the wafer and is focused by a series of lenses onto the wafer below. In direct overlay or proximity systems, a mask the same size as the desired integrated circuit is placed directly over the silicon wafer and exposed to the light. Projection systems allow greater resolution and overlay capability and are used in most current systems, but may require sophisticated optics for future, higher-resolution systems.

(continued *on next page)*

IC technology. Lithography process control, for instance, requires that lines and spaces be measurable to within one-third of the minimum dimension. The present realistic capability for wafer measurements is O.15 micron. Therefore, new measurement methods must be developed to control processes with critical dimensions less than 0.5 micron to ensure adequate process control.

Measurement capability also limits process characterization. For example, surface measurements required to evaluate materials growth and etch processes limit modeling and characterization of these important processes. The inability to accurately analyze residual gases in process chambers is a major impediment to understanding chemical plasma processes. Similarly, metrology limits the device structure evaluation; today's methods for measuring vertical device structures cannot accurately resolve the sharp impurity gradients of the shallow junctions used in 0.25-micron processes.

Advances in metrology are necessary for improvements in contamination control. Present measurement techniques are capable of detecting 109 (one billion) heavy metal contaminant atoms per cm^2. Process controls required to achieve competitive process yields 15 years from now will require detection of 10^7 (ten million) atoms per cm^2. Advanced IC fabrication requires meas-

Box 3-A--Advances in Lithography--Continued

Current production-level lithography systems operate at optical wavelengths of light, typically either 436 nanometers (G-line) or 365 nanometers (I-line), generated by mercury vapor lamps. They yield a resolution of about 0.5 micron. Smaller linewidths will require shorter wavelength light, in the "deep ultraviolet" portion of the spectrum (248 or 193 nanometers), generated by excimer lasers. These wavelengths could generate linewidths as narrow as 0.18 microns, but difficulties in narrowing the depth of focus and diffraction could limit their applicability y past 0.25 microns. Alternative technologies may need to be sought.

One possibility is x-ray lithography, which uses significantly shorter wavelengths of light (about 5 nanometers), but otherwise operates much like an ultraviolet system. Proximity x-ray systems have been studied for several years, but require a bright source of x-rays such as a synchrotrons and cannot offer the resolution of projection systems. The latter constraint could limit proximity x-rays from being used past 0.18 microns. More recently, research has begun to focus on projection x-ray systems, which could offer linewidths of 0.12 micron or less and rely on less expensive sources of x-rays. Development of such systems would require significant advances in the manufacture of the necessary optics, a process that requires the creation of multiple-layered films with precisely controlled thickness.

Alternatively, smaller linewidths could be achieved with electron beam or ion beam techniques in which beams of high-energy electrons or charged particles (ions) are fired at the surface of the wafer. E-beams have demonstrated resolution as small as 2 nanometers in certain materials in a laboratory setting,[1] but are limited in their applicability to full-scale production lines because they can draw lines only one at a time. Ion beams can generate linewidths as small as 100 nm, but, as with e-beams, must be scanned across the entire wafer surface one step at a time. Research is being conducted on methods for increasing the throughput of such direct-write systems, but is still in the early stages.

[1] U.S. congress, Office of Technology Assessment, *Miniaturization Technologies*, OTA-TCT-514 (Washington, DC: U.S. Government Printing Office, November 1991), p. 37.

urement capabilities consistent with tight process controls. Advances in the science of measurement (i.e., metrology) are important to both semiconductor producers and equipment suppliers.

Sensors For Process Control

New low-cost, reliable, and sensitive sensors are necessary to increase the rate of learning in tool development, reduce the time to market for process equipment, improve tool and process controls, increase process yield, and reduce defects.

Greater use of real-time, in situ sensors is driven by economics. Sensors are the critical elements in closed-loop process control and are necessary for detecting process problems when they occur, so that corrective actions can be taken immediately. Sensors are also required to improve frost-pass success when introducing process variations.

Accurate control of even such commonly used processes as rapid thermal processing (RTP) and plasma deposition and etch requires new sensor approaches. The technique used to control todays RTP equipment (called back surface emission), for instance, leads to 50 to 200 degree Celsius temperature errors. Reliable RTP control requires new temperature sensors that are more accurate and more responsive to real-time front surface conditions.

Sensors that monitor gas and chemical purity and cleanliness are also of major concern. Gas analyzers, mass controller calibrators, chemically selective sensors, and particle detectors are all essential to maintain process cleanliness. Environmentally conscious manufacturing will require recycling and reuse of chemicals not only to minimize waste, but also to reduce cost. Chemical generation and reuse will require sensors that can detect impurities at a parts per billion level for on-line monitors of chemical purity.

Modeling and Simulation

IC technology has developed faster that the capability for modeling and simulating its various elements. Cost and complexity of IC fabrication make the acquisition and application of advanced modeling and simulation tools an imperative.

Computer-based modeling and simulation have become essential in all areas of semiconductor technology. Models are now used for materials, devices, and processes, as well as for circuits and systems. In addition, entire fabrication equipment systems—from process chambers and wafer handling systems to the design and operation of complete factories-require modeling and simulation.

The physics base for models is still incomplete. Today's modeling and simulation tools are unreliable, incompatible with one another, and unable to cover the entire range of requirements. But, modeling and simulation are critical to the IC industry because of the need for faster implementation of error-free designs for chips, systems, and factories. Modeling and simulation have pervasive applicability and provide the tools necessary in the design, test, and production of materials, equipment, processes, factories, devices, systems, packages, circuits, and ICs.

The highly complex task of developing suitable models requires a vast range of skills, from physics and chemistry to electrical/mechanical engineering and computer science. These skills are developed in environments such as national laboratories, universities, computer systems producers, and the semiconductor industry.

Reliability and Quality

Existing manufacturing methods do not ensure reliability and quality of complex semiconductor products, particularly where the physical limits of the materials, processes, and structures are challenged. In submicrometer structures, processes and structures are being pushed to the physical limits of breakdown voltage, interconnect current-carrying capacity, stress, defect and contamination levels, alignment errors, and noise margins. Shallow junctions, trenches, stacks, capacitors, new device architectures, and ultra-thin interconnect lines each introduce new failure possibilities.

Commercial success of semiconductor technology in all applications depends on reliable, long-term performance to specification. With current technologies, however, the reliability of submicrometer devices cannot be determined in advance. A systematic approach to reliability engineering must be therefore be developed. Standard test environments, based on design rules and fabrication conditions, must be available to the entire IC community. Standard tests applied to standard test structures will simplify the interpretation and comparison of the resulting data. As they affect reliability, the roles of microstructure, topography, and stress must be determined. Both empirical and fundamental models must be developed and experimentally confined. Techniques such as design-for-reliability and an understanding of the relationships between process contamination and reliability are essential to a systems approach to reliability and quality.

Contamination-Free Manufacturing (CFM)

Impurities and particles are unintended contaminants in all IC manufacturing steps. Sources of contamination, which include processing materials (including chemicals and gases), process chambers, wafer handling systems, and facilities, contribute to reduced IC process yields. As products and process complexity increase, the size and density of defects or impurities must be substantially decreased.

IC producers expect to achieve yields close to 100 percent to meet cost and reliability goals. This requires processes, materials, equipment, and new fabrication facilities to be defect-free. A clear understanding of the generation, detection, and elimination technologies for unwanted impurities and particulate is critical.

Manufacturing-Critical Software Engineering

IC manufacturing process equipment is increasingly regulated by software-programmed controllers. Software failures are a major problem for today's fabrication equipment. This problem will worsen with greater equipment and factory automation. Provisions for the creation, upgrade, and maintenance of equipment and factory software are essential.

Improved software design for reliability and testing is key to efficient maintenance and reduced equipment failure rate. Developers of equipment control architectures must look beyond immediate applications to include expandability for future applications. Self-testing codes, modular structures to provide flexibility, use of efficient high-level languages, noise immunity, and interrupt timing standards are all important to improve software performance and reliability in the semiconductor factory. Other manufacturing-critical software-related issues include manufacturing databases, logistics planning, and factory and equipment control. These factory system applications must interact closely with equipment.

costs

The technical challenges outlined above will not only stretch the scientific and engineering talents of U.S. semiconductor manufacturers, they will also stretch their financial resources. R&D and production facilities are becoming more costly to the semiconductor industry, and without a radical change in manufacturing technology will continue to rise on their current trend lines. With product life cycles as short as three or four years for most semiconductor products, large investments in R&D and capital must be continually maintained. Although costs of capital seem to be converging in the United States and Japan, U.S. manufacturers may still beat a disadvantage compared with international rivals who often receive direct government support of commercial technology development and whose industry structure is more tolerant of large investments with longer payback periods. In the absence of other mechanisms, U.S. companies may be forced to enter into more strategic alliances to pool resources with other companies, both at home and abroad.

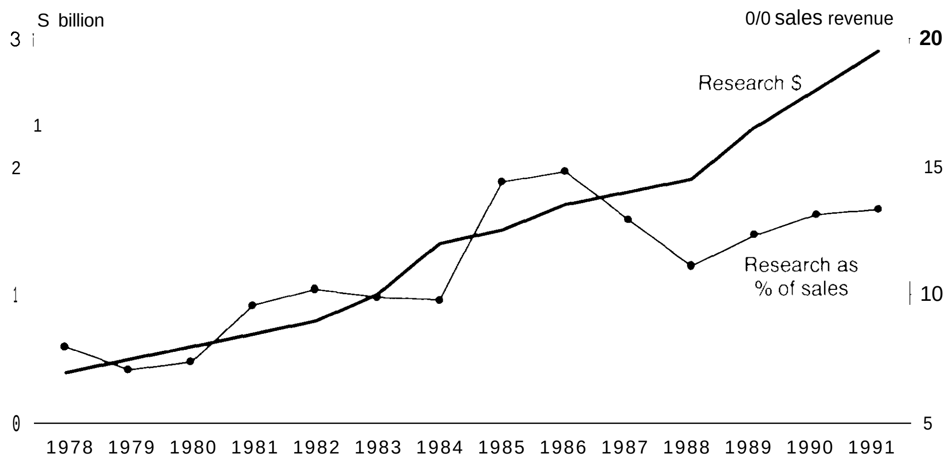
R&D

In order to remain competitive, U.S. manufacturers will have to maintain high levels of spending on R&D. The rapid pace of innovation in the semiconductor industry requires such investments to support new product and process development. As competition has grown, U.S. companies have been forced to increase their R&D spending. Between 1980 and 1991, annual R&D expenditures by U.S. merchant producers increased by a factor of five, from $600 million to $2.9 billion. This growth in R&D has far outpaced gains in sales revenues, reflecting the increasing R&D intensity of semiconductor manufacturing. As a result, R&D expenditures as a percent of sales increased from 7.4 to 13.3 percent since 1982 (figure 3-13). The semiconductor industry is now the most R&D-intensive of all major industrial sectors except computer software and services (figure 3-14).

Production Facilities

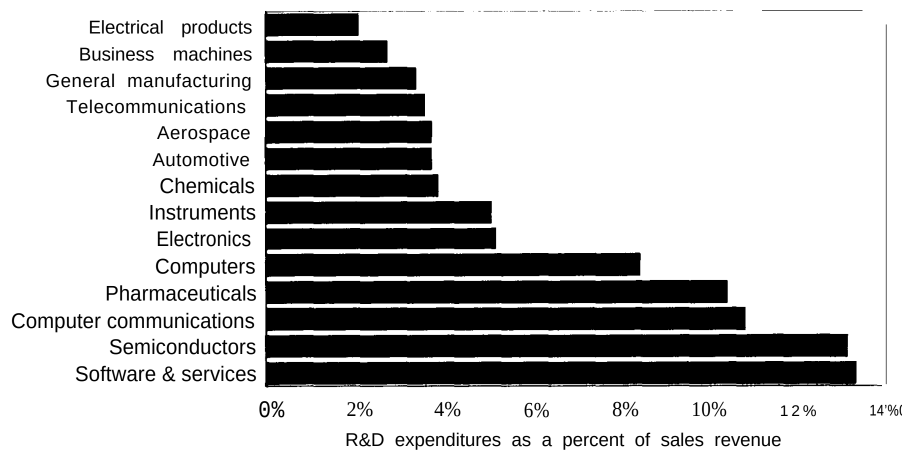
Cost for new production facilities are likely to continue growing over the next decade. Due to rising equipment costs and the increasing number of processes required for each new generation of semiconductor chip, the cost of a state-of-the-art wafer fab has risen from $25 million in 1989 to over $500 million in 1992, and is expected to

Figure 3-13—Sales Revenues and Expenditures on R&D in the U.S. Semiconductor Industry



SOURCE: Semiconductor Industry Association, *Annual Databook: Global and U.S. Semiconductor Competitive Trends—1978-1991* (San Jose, CA: Semiconductor Industry Association, 1992), p. 41.

Figure 3-14—R&D Expenditures in Key Sectors of U.S. Industry



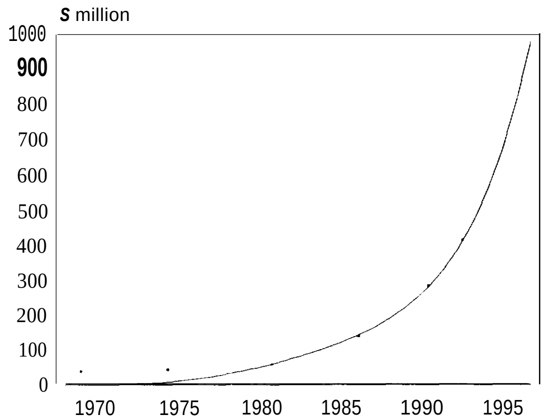
SOURCE: Semiconductor Industry Association, *Annual* Databook: *Global and U.S. Semiconductor Competitive Trends—1978-1991* (San Jose, CA: Semiconductor Industry Association, 1992), p. 42.

exceed $1 billion by 1995[50] (figure 3-15). About 75 percent of this cost is associated with fabrication equipment as opposed to land and buildings.[51] Processing a typical wafer now requires over 300 steps, conducted on hundreds of pieces of semiconductor manufacturing equipment, each of which can cost between $200,000 and $3 million, and each of which must be maintained in a clean environment that allows fewer than one O. 15-micron particle per cubic foot.

50 Wafers are disks of silicon on which hundreds of semiconductor chips are simultaneously produced.

51 Semiconductor Industry Association, *Annual Databook: Global and U.S. Semiconductor Competitive Trends, 1978-1991 (San Jose,* CA: Semiconductor Industry Association, 1992), p. 38.

Figure 3-15-Growing Cost of a Wafer Fabrication Facility



SOURCE: Arati Prabhakar, Advanced Research Projects Agency, "Flexible Intelligent Microelectronics Manufacturing," briefing to OTA on June 15, 1993.

Moreover, the rapid pace of technological innovation in the semiconductor industry requires companies to make these large investments in plant and equipment on a regular basis. New facilities may become outdated after only three years of operation. While they may then be used to produce other types of devices that do not rely on state-of-the-art processes, much of the equipment cannot be modified for next-generation chips. The advantages gained by being first to market (cost reduction through learning curves, market expansion) pressures companies to bring new facilities on-line rapidly.

Some alleviation of cost and economy of scale considerations could be achieved with more flexible manufacturing equipment. ARPA recently completed a program entitled Microelectronic Manufacturing Science and Technology (MMST) that investigated the economic benefits of flexible manufacturing systems to semiconductor manufacturers and developed rudimentary systems for flexibly processing small batches of wafers. Such technologies appear capable of reducing the economies of scale necessary for an efficient plant, but are applicable primarily to small batch manufacturing and will thus remain outside the purview of mainstream semiconductor manufacturers for some time.

ALTERNATIVES FOR FUTURE R&D

The high costs associated with continued success in the semiconductor industry are rapidly exceeding the financial capabilities of individual companies. Moreover, the long-term nature of the required investments exceeds the planning horizons of most U.S. corporations. In recent years, many companies have redirected their research dollars to short-term projects focused on near-term product development. The two U.S. companies that had formerly filled the gap between university research and corporate product development by focusing on initial prototype development, IBM and AT&T's Bell Laboratories, have redirected their R&D dollars to link research programs more closely to product development activities.

In order to make up for this growing deficiency, semiconductor companies have entered into strategic alliances with domestic, or more typically international, partners to pool their resources with other companies and share the risks associated with large R&D programs. An alternative source of R&D funding would be the federal government. The end of the Cold War provides an opportunity for the government to redirect its investment in defense technologies to programs more closely tied to commercial competitiveness. In this realm, federal laboratories may provide a key link in the R&D cycle.

Strategic Alliances

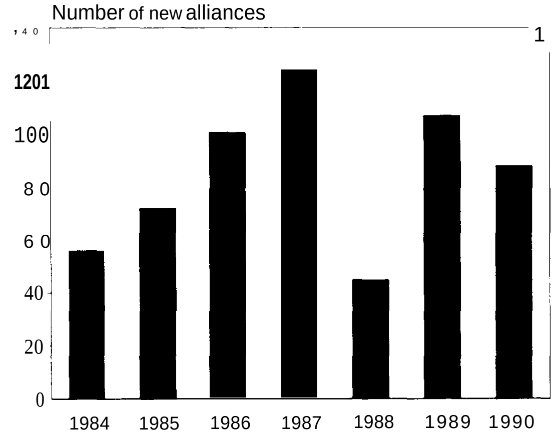
Many companies are financing R&D projects and production facilities in part through strategic alliances with domestic or international partners. While strategic alliances are not new to the semiconductor industry, their number has increased and their character has changed over the past decade. Throughout the 1970s and into the early 1980s, alliances between U.S. and Japanese companies were few and involved the licensing of technology from small U.S. companies that lacked capital and manufacturing facilities to larger Japanese fins. By the late 1980s, the number of publicly announced strategic alliances announced each year had risen to about 100, about half of which, in 1990, were joint development agreements, joint fabrication agreements, or other types of joint ventures (figure 3-16).[52]

Strategic alliances are also becoming more prevalent among large U.S. semiconductor manufacturers such as IBM, Motorola, and Intel as development and production costs continue to rise, straining the financial resources of these companies. For example, IBM, Toshiba, and Siemens A.G. have teamed to develop technology for 256-M DRAMs, the cost of which no company could individually afford, given the low profit margins associated with memory devices. Similarly, Advanced Micro Devices Inc. and Fujitsu Ltd. agreed to establish a $700-million state-of-the-art joint fab for producing a new type of memory device called ''flash memories. '

These alliances allow companies to pursue technologies that might otherwise be too expensive to develop alone, and they provide ways of tapping into additional pools of funding. This is of interest not just to U.S. firms, but to Japanese companies as well. Overcapacity and a weak economy in Japan have pushed Japanese semiconductor manufacturers' capital spending levels down 29 percent in 1992; spending is expected to fall another 13 percent in 1993. Capital expenditures are likely to rise in North America by 13 percent in 1993, due in large part to a 25-percent increase by Intel Corp.

However, alliances raise concern about the possible transfer of U.S. technology abroad. Alliances are typically structured to team up U.S. technology and strengths in design and innovation with Japanese manufacturing capability. While the transfer of the product technology to Japan can be fairly easily accomplished, the transfer of manufacturing know-how back to the U.S. is more difficult. With manufacturing taking place in Japan, U.S. partners have difficulty learning from their Japanese partners. Therefore, such alliances may be more beneficial to Japanese companies than to U.S. companies. A recent report by the National Research Council warns that a continuation of strategic alliances of the kind found today in the semiconductor industry may prevent both the United States and Japan from developing the complementary capabilities they seek in their alliances.[53]

Figure 3-1 6-U.S.-Japan Semiconductor Alliances, 1984-1990



SOURCE: Bruce Kogut and Dong-Jae Kim, "Strategic Alliances in Semiconductor Firms," report to Dataquest, January 1991.

Greater Industry/Government Collaboration

An alternative to strategic alliances would be a greater government role in supporting semiconductor R&D and/or production. The government has many facilities capable of conducting research relevant to the semiconductor industry. With the end of the Cold War, resources that were

[52] The number of actual alliances may be considerably larger than the number announced, perhaps by a factor of two or more. National Research Council, *U, S.-Japan Strategic Alliances in the Semiconductor Industry* (Washington, DC: National Academy Press, 1992), p. 32.

[53] Ibid, pp. 2-3.

formerly devoted to defense missions maybe able to serve commercial purposes. The Department of Defense and the Department of Energy laboratories could serve as collaborators with industry on new technology development. NIST, which already has a mission to support industry, has developed a series of plans targeted to foster and support technological advances in the semiconductor industry.