# Semiconductors: the building blocks of the information revolution

*Driven by advances in technology and an ever-growing demand, job growth and earnings in the semiconductor industry are above those of manufacturing as a whole*

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The U. S. semiconductor industry is renowned for its record of technological breakthroughs. These advances have increased the speed and capabilities of computer chips and led to employment growth in the industry that runs against the grain of recent U. S. manufacturing history. On the demand side, this feat has been sustained by an apparently insatiable worldwide demand for what is the enabling technology of computers, telecommunications equipment, and consumer electronic products. Indeed, semiconductor companies produce the very building blocks of the information revolution.

Semiconductor producers are also engaged in a costly, worldwide race of technology development evident in the continuous flow of advanced products, high research and development (R&D) expenditures, and expensive fabrication facilities. This has required a growing, highly trained work force, with hourly earnings substantially above the average in manufacturing. In 1995, the industry employed 236,000 workers, 10 percent more than in 1993.

Interaction between technology and employment in semiconductor manufacturing affect worker productivity, offshore employment, technology diffusion, and R&D employment. Following a background section, the discussion covers three major topics: the organization of the industry (including a geographic profile of production and employment), employment and trade, and manufacturing technology and labor (including the economics of chip assembly and the cost structure of the industry). The final section contrasts a recent slowdown in the semiconductor market with the positive long-term outlook based on industry expansion plans.

## What are semiconductors?

Semiconductor devices are the basic functional components of computers and other electronic products. They are based on materials, such as silicon, that conduct electricity with less facility than perfect conductors; small changes in their physical structure often induce significant changes in their electrical properties. This makes these materials extremely versatile because their electrical properties can then be customized to create new applications or improve performance.

The industry's products include discrete semiconductors and integrated circuits. Discrete semiconductors are semiconductors with a single component like a transistor. These products are used as components in electronic circuits.[1] Integrated circuits (IC), or computer chips, are pieces of silicon wafers that incorporate complex electronic circuits. They can contain millions of transistors and other components. In terms of shipments, the major products are IC's, including microprocessors and memory chips. These products are available at several levels of integration: from chip sets to computer motherboards and modules.

Microprocessors function as the central processing unit of a computer. They vary in speed and the ability to do a variety of logical and mathematical functions. These features are determined primarily by the number of transistors per chip.

Transistors in an IC translate information into bits or on/off switches.[2] This allows the computer to write and manipulate data by simply controlling a flow of electric signals. Memory chips[3] store information and can be characterized by capacity (bits/chip) and speed.

Semiconductors and computers are interdependent in the marketplace as well as in the design lab. Computer demand is driven by the desire for higher speed and increased functionality.[4] This in turn, is determined by the system design and the underlying capabilities of its components. At the same time, the semiconductor industry is driven by the competitive pressure created by computer design cycles of 6 to 12 months. In turn, this translates into the demand for ever-faster and more versatile chips, resulting in more jobs in semiconductor R&D and production.

## The industry

The electronics industry (electronic and other electrical equipment, SIC 36), with 1.62 million employees in 1995, is one of only seven manufacturing industries employing more than a million workers. Electronic components manufacturing (SIC 367) is the largest employer in the electronics industry and semiconductor plants (SIC 3674) employ more than 40 percent of electronic components workers. Semiconductor jobs have more than doubled since 1972, the starting date of the employment series for this industry. (See table 1.)

The semiconductor industry is composed of firms that design, manufacture, and market semiconductor devices for original equipment manufacturers and for personal computer (PC) users. Semiconductors control and amplify electrical signals in many electronic products. These include computers; TV's, VCR's, and other home appliances; telecommunications equipment; industrial machinery; aircraft; and military equipment. Computers and telecommunication products consume more than three-fourths of U. S.-made chips.

U. S. semiconductor companies are major players in the electronics industry and the global economy. According to the Semiconductor Industry Association, in 1994, they held 50 percent of the European semiconductor market, 40 percent of the Asia/Pacific market, and 17 percent of the Japanese market. The Association's data show that the worldwide semiconductor market was valued at $144.4 billion in 1995. The North American market consumed $46.9 billion, or 32.5 percent.[5] As an indication of how rapidly the industry is expanding, the Association estimates the 1996 worldwide and North American markets at more than $154.0 and $50.6 billion, respectively. The industry exhibits a continuous flow of new products, rapid erosion of prices, short product cycles, and cyclical demand.

**Table 1. Employment in electronic equipment, electronic components, and semiconductors, 1972 and 1995 annual averages**

[Numbers in thousands]

| SIC number | Industry | 1972 | 1995 | Percent of SIC 36: 1972 | Percent of SIC 36: 1995 | Percent growth |
|---|---|---|---|---|---|---|
| 36 | Electronic equipment | 1,535.0 | 1,624.7 | ... | ... | 5.8 |
| 367 | Electronic components | 345.1 | 581.7 | 22.5 | 35.8 | 68.6 |
| 3674 | Semiconductors | 115.2 | 236.0 | 7.5 | 14.5 | 104.9 |

The organizational structures of U. S. semiconductor firms vary according to size and degree of specialization. Some of the larger semiconductor manufacturing firms have chip design facilities and large R&D departments; many of these have technology centers that provide customer support. So-called chip foundries are semiconductor manufacturers that do not have in-house chip design capabilities. They manufacture under contract for other chip companies with small or no manufacturing facilities—a practice known as contract manufacturing. It involves mostly commodity chips (low-cost, high volume IC's such as DRAM's).[6] Some firms, often start-ups, specialize in research and product development and have a small staff. Integrated circuit engineering firms are mostly small service firms that perform design work for chip manufacturers. Foreign firms in the United States, including Japanese, South Korean, and European firms, have production or chip design facilities on their own or jointly with U. S. partners.

Semiconductor firms, whether they are integrated firms, R&D start-ups, or chip foundries, can have different positions in the industry structure. (See exhibit, page 8.) Some firms manufacture almost exclusively semiconductor products. Semiconductor divisions of large computer, electronics, and aerospace companies manufacture both semiconductor devices and complete electronics products and systems. Other companies show backward integration—they manufacture not only computer chips, but also silicon wafers, the starting material of chips, for both internal use and the merchant market.

Firms that manufacture complete computer systems, storage devices (such as hard disks and CD-ROM's), and peripheral computer equipment have a close relationship with semiconductor firms. Increasingly, the high demand for chips from these firms requires unwieldy arrays of chip suppliers and delivery schedules. Some eventually establish joint manufacturing ventures with their semiconductor suppliers. These joint ventures enable chips to be made with the latest technology at lower cost and with direct control over product quality and delivery schedules. Typically, the staff is a combination of loaned keyworkers from the parent companies and new hires. Overseas joint ventures provide an additional venue for U. S. semiconductor jobs.

In technology agreements, such as licensing of technologies or products, firms share key personnel to develop a manufacturing technique or a product. Sometimes these agreements involve participation in stock ownership and are preludes to acquisitions or mergers. Both provide a competitive edge by complementing manufacturing and technology strengths,[7] sometimes accompanied by job transfers or layoffs. However, mergers have not been a significant source of employment change in semiconductors recently.

The many relationships among semiconductor firms have different employment impacts. For example, contract manufacturing increases efficiencies at the industry level between research powerhouses and volume producers. (See section on costs below.) This practice affects U. S. semiconductor employment whenever the chip foundry is located offshore. However, as discussed later in this article, advances in technology may alter the economics of offshore chip manufacturing.

## End markets

The United States and Japan are the largest semiconductor markets with 32.9 percent and 28.9 percent, respectively, of worldwide consumption. The computer market is the largest semiconductor user in both the United States and Japan. (See chart 1.) The high-end sector of the computer industry is one end user willing to pay for the latest generation of integrated circuits and other semiconductor products. Therefore, any country dominating semiconductor R&D is likely to dominate the computer sector of the semiconductor market. The United States has maintained its leading position in sophisticated microprocessors, while largely leaving the commodity DRAM market.[8]

Reflecting the size of the Japanese consumer electronics manufacturing industry, the consumer segment is the second largest end user of semiconductors in Japan, whereas it is a distant fifth in the United States. As can be seen in chart 1, end-use market shares are more evenly distributed in Japan, compared with the United States.[9] This is an advantage when it comes to weathering demand slumps in certain sectors of the market.

## Geographic profile

*United States.* Silicon Valley has become a household name since the early 1970s, when the chipmakers and computer designers gave fame and fortune to the San Jose-Palo

Exhibit 1. **Structure of the U.S. semiconductor industry, with examples of major companies**

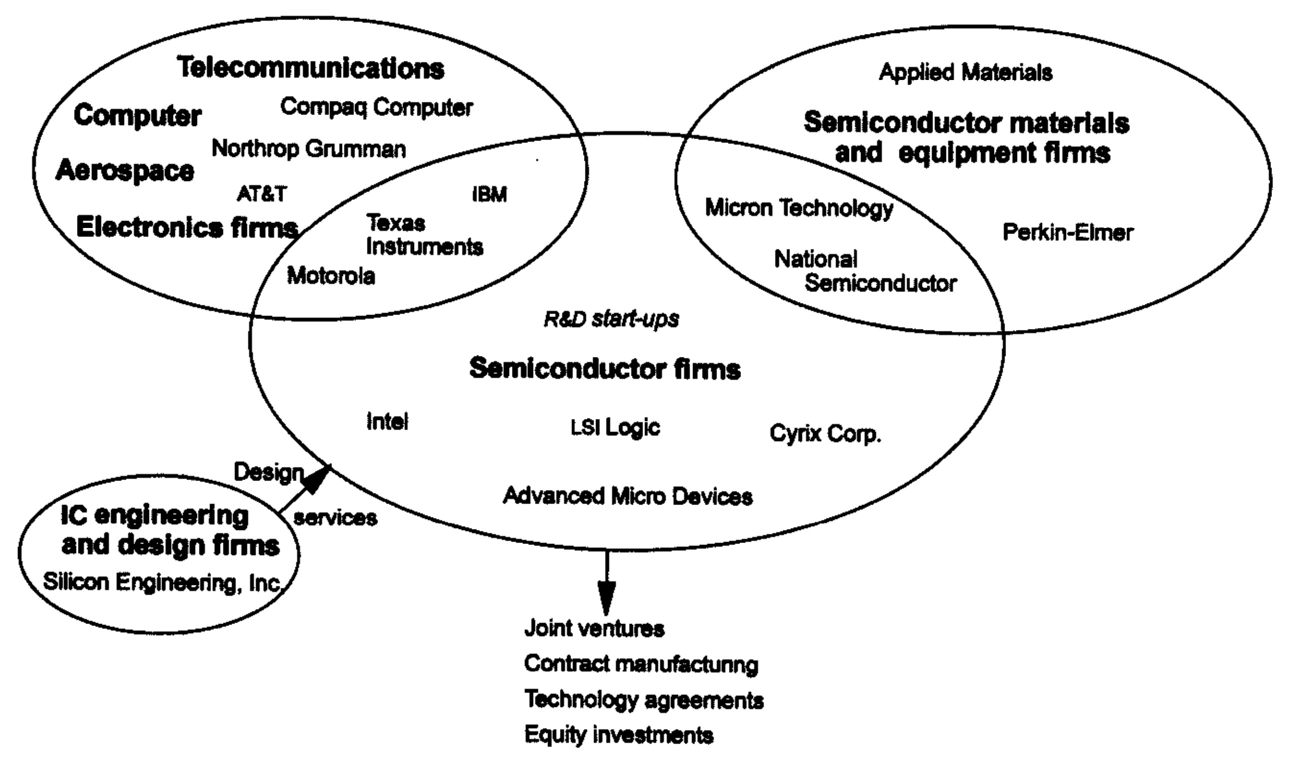
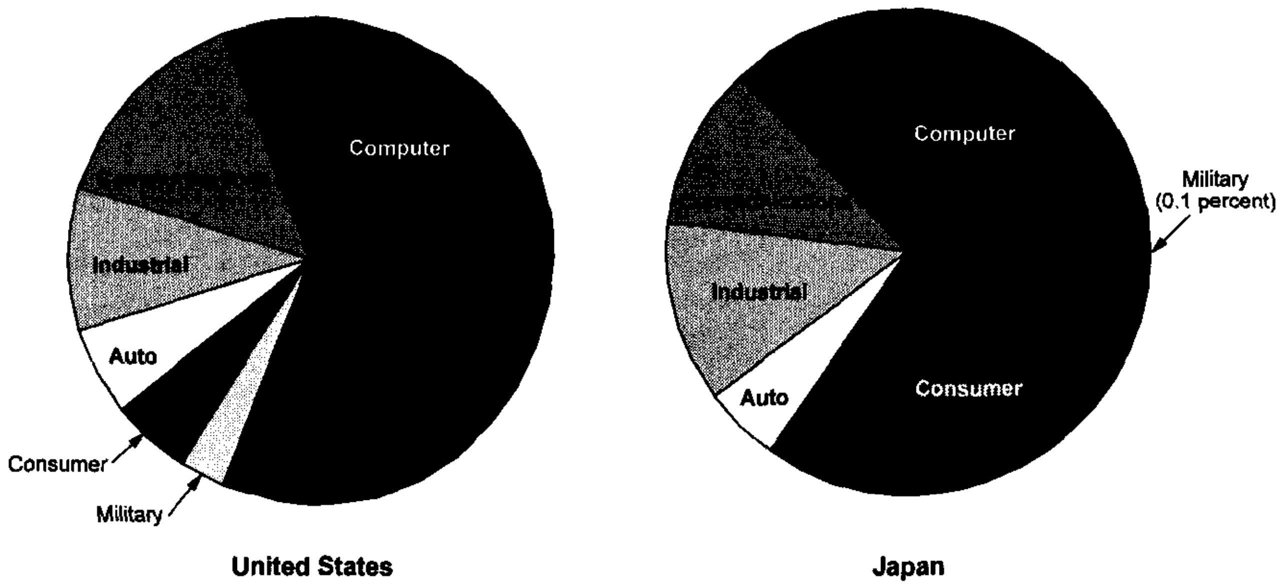


Chart 1. **Semiconductor markets, by percent end use, United States and Japan, 1994**




SOURCE: Based on data from the Semiconductor Industry Association.

Alto corridor in California. In fact, California is the Nation's largest semiconductor producer and employer. There are more than 1,100 semiconductor establishments nationwide, but almost half of the industry's 1994 employment is concentrated in three states: California, Texas, and Oregon.[10]

Suppliers of materials, computer makers, and other electronic firms often locate in a given region to take advantage of pools of highly skilled labor-like electronic engineers and computer programmers. Others go to low cost areas, and meet employment needs with local and out-of-State college graduates and workers. This has generated competition among States for semiconductor companies, given that a single chip plant can create several thousand jobs and attract related high tech firms. 'Silicon Forest' in Oregon is emerging as an area with a high concentration of semiconductor companies, with more than $13 billion in high-tech construction either planned or underway between Portland and Eugene. A State economist predicts that at least 25,000 chip-related jobs will be added to Oregon's payrolls by the end of the decade. [11]

*Worldwide markets.* The spread of technology and differences in overall costs of production have shaped the worldwide semiconductor market into four regions with two major tiers. (See chart 2.) The first tier—composed of the United States and Japan—are about equal in semiconductor market share (about 30 percent each). They exchanged leadership roles in 1982 and 1994. The second tier is composed of the Asia/Pacific countries and Western Europe, which share equally the remaining 40 percent of the market. European market shares have been mostly flat since 1982. The market share of Asia/Pacific countries increased steadily between 1982 and 1994, to about a fifth of the market.

U. S-based firms employ about half of their work force in facilities abroad, according to the Semiconductor Industry Association. Many U. S. firms compete on a worldwide basis and have production and marketing facilities in all four regions mentioned above. The production process of an IC entails tradeoffs among different capital and labor intensities. U. S. semiconductor firms perform research and development, product design, and wafer fabrication mostly in U. S. facilities. On the other hand, a good share of product assembly and testing is done in offshore facilities, especially in Southeast Asia.[12] The finished products are either imported back to the United States, where they are subject to import duties only on value added abroad or exported to a third country. In addition, some U. S. semiconductor firms have plants in low-cost European countries such as Ireland, and in Israel.

There are several factors behind technological diffusion in the semiconductor industry. Global research and production activities, often on a joint-venture basis, are major factors. In addition, licensing and developing chip clones are common industry practices. Manufacturing standards, in terms of semiconductor equipment and procedures, also contribute to technology diffusion. Although technology diffusion is a prerequisite for high-tech employment diffusion, it does not ensure it. A foreign location may be economically attractive in terms of overall production costs, but these advantages are not likely to be sustainable without a well-trained labor force.

## U.S. employment and trade

Employment data for the U. S. semiconductor industry, collected since 1972, are available from the Bureau of Labor Statistics Current Employment Statisics program. (See chart 3.) Employment boomed between 1975 and 1985 in response to the creation of the first microprocessor in the early 1970s and the production of the first IBM PC in 1981. Advances in IC technology and computer design spurred the birth of new firms, increased production, and nurtured employment growth. (See the box, below.)

The all-time high of almost 300,000 semiconductor workers in January 1985 was reached amid a robust economy. However, this level of capacity and employment was unsustainable through subsequent cycles. Employment levels declined from 1985 to 1993, in spite of a brief uptick in 1988. U. S. sales of semiconductor products totaled $46.9 billion in 1995, up 40

## Genesis of a tiny giant

The emergence of the semiconductor industry can be traced to the commercial launch of the transistor in 1951. These early semiconductors substituted for vacuum tubes in many electrical functions. Three types of firms initiated the industry in the early 1950s: vacuum tube producers such as RCA and Sylvania; divisions of large electronic firms such as IBM and Western Electric; and new firms such as Texas Instruments. (See J.E. Tilton, *International diffusion of technology: the case of semiconductors* (Washington, D.C. The Brookings Institution, 1971.)

Early telephone exchanges and computers used vacuum tubes as the main functional component. The transistor is more efficient than vacuum tubes in that it uses less power, generates less heat, and is smaller. This allowed smaller, more reliable electronic circuits that, in turn, boosted the production of many electronic products and made smaller computers possible. The integrated circuit (IC) is the latest major step in the drive toward smaller size, improved reliability, and an increased number of computing functions. The IC was invented by Robert Noyce of Fairchild and Jack Kilby of Texas Instruments in 1958, and put into commercial production in 1961. Today, computers and many electronic products are based on IC technology.

Key scientists and other technical personnel who moved on to exploit a new product have always been an important factor in the semiconductor industry. For example, the inventor of the transistor, William Shockley, established a small research firm after leaving Bell Laboratories in 1954. Fairchild Semiconductor, one of the birthplaces of the IC, spun off Shockley's firm in 1957. And in 1968, Robert Noyce left Fairchild and founded Intel, one of today's industry leaders. (See Tilton, *International diffusion.)*

In 1971, Intel created the first microprocessor chip, the Intel 4004, which contained more than 2,000 transistors. The 4004 was a 4-bit microprocessor, that is, it could process four bits of information at a time. The 8-bit 8008 and 8080 microprocessors were introduced in 1972 and 1974, respectively. The first microcomputers, offered for sale in 1975, used the 8080 microprocessor, and IBM's first personal computer used an Intel 8088 processor in 1981. (See Les Freed, *The history of computers,* Emeryville, CA, Ziff-Davis Press, 1995.) Besides Intel's Pentium and Pentium Pro, current chips include IBM's Power PC chip, and the Ultra Sparc chips (Sun Microsystems) and the Alpha chips (Digital Equipment Corporation) for the workstation market.

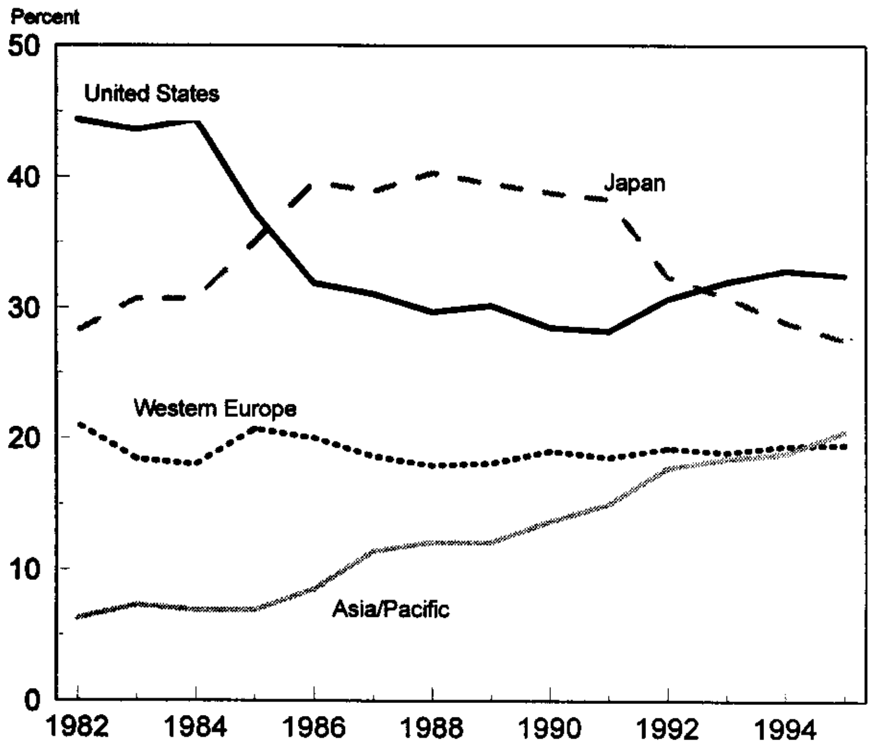
The evolution of the microprocessor, the result of an intense research and manufacturing agenda, is summarized below.

**Evolution of the microprocessor**

| Year | Central processing unit (CPU) | Transistors (thousands) | Million of instructions per second | Word size (in bits) | Price at introduction | Application at introduction |
|---|---|---|---|---|---|---|
| 1971 | 4004 | 2.3 | 0.06 | 4 | $200 | Basic calculator |
| 1974 | 8080 | 6 | .64 | 8 | 360 | Intelligent terminals |
| 1978 | 8086 | 29 | .75 | 16 | 360 | MS-DOS, CP/M PC's |
| 1982 | 80286 | 134 | 2.66 | 16 | 360 | Multitasking, multiuser |
| 1985 | 80386 | 275 | 6 | 32 | 299 | Multitasking, multiuser |
| 1989 | 80486 | 1,200 | 20 | 32 | 950 | High-end multitask |
| 1993 | Pentium | 3,100 | 100 | 32 | 965 | High-end multitask |
| 1995 | Pentium Pro | 5,500 | 250 | 64 | 1,200 | Workstations, server machines |

SOURCES: Freed, *The history of computers*; Intel Co. Archives at www.intel.com; and *The Wall Street Journal.*

Chart 2. **Regional semiconductor market shares, 1982–95**




SOURCE: Based on sales data from the Semiconductor Industry Association.

percent from 1994. Production jumped by 27 percent over the same period. Data Resources Inc. (DRI) projects that real U. S. semiconductor output will grow by 7.9 percent annually between 1993 and 2005, the highest growth rate among all industrial and consumer products in the DRI model.[13]

With the exception of 1990–91, the industry experienced either large trade deficits or declining trade surpluses from the mid-1980s to early 1990s. This was also a period when semiconductor employment declined. The continued technological prowess of U. S. firms, aided, perhaps, by the Semiconductor Trade Agreement of 1986, reversed these trade deficits gradually. (See chart 4.) However, this did not translate immediately into job growth. Most of these deficits were related to the emergence of Japan as a global semiconductor exporter and by difficulties that firms had in entering the Japanese market. The trade agreement established conditions to open the Japanese semiconductor market to foreign makers.[14] The market share of U. S.-based merchant semiconductor firms in Japan's market increased from approximately 10 percent in 1990 to more than 17 percent in 1994, even as that market increased from $19.6. billion to $29.4 billion. Still, in 1994 the American share was below the 23 percent held by Japanese firms in the U. S. market. In addition, while U. S. firms had a 65-percent share of their home market, Japanese firms hold 78 percent of the Japanese market.

By 1990, the United States had a trade surplus, but this lasted only 3 years. In 1995, after 2 years of deficits below the billion dollar mark, the industry showed a trade deficit of $4.74 billion. Last year's deficit can be attributed more to capacity shortages and record chip demand by firms doing business in the United States than to trade woes: a solid 35-percent increase in exports just could not offset a 50-percent increase in imports. Japan, Canada, and several Southeast Asian newly industrialized countries are the major trading partners of the U. S. semiconductor industry. Canada is the largest export market with 16 percent of shipments, followed by Malaysia, Japan, Singapore, and Taiwan. Japan represented 27 percent of imports, or $10.7 billion, in 1995. Another 50 percent of imports comes from South Korea, Malaysia, Singapore, Taiwan, and the Philippines. (Recall, though, that some imports are products assembled from American-made parts by U. S. subsidiaries or contract manufacturers.)

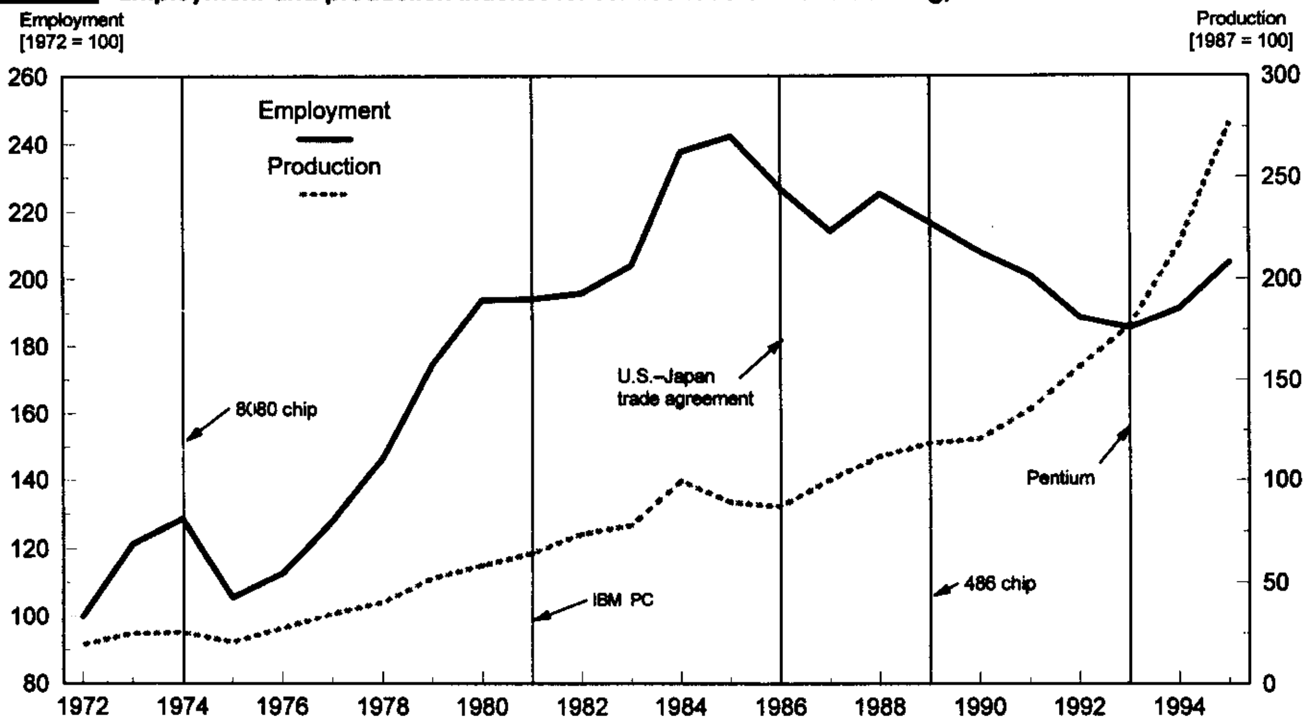
Trade deficits notwithstanding, exports of semiconductors have increased steadily since 1985. In fact, by 1995, exports more than doubled from 1992 levels.[15] Not surprisingly, exports generate a significant number of jobs in this industry. A study by the Commerce Department estimated that U. S. employment in semiconductor manufacturing that was supported by exports grew 25 percent from 1983 to 1992.[16] The study also found that 120,000 semiconductors jobs, or about half of all U. S. semiconductor jobs, were supported by exports in 1992.

Jobs in the semiconductor industry have increased more than 20 percent since its latest trough in June 1993—although manufacturing as a whole has been losing workers. To explain this strength and the likelihood of its duration, the next section analyzes how advances in semiconductor technology have shaped U. S. production into capital and R&D intensive activities that demand highly skilled workers.

## How chips are made[17]

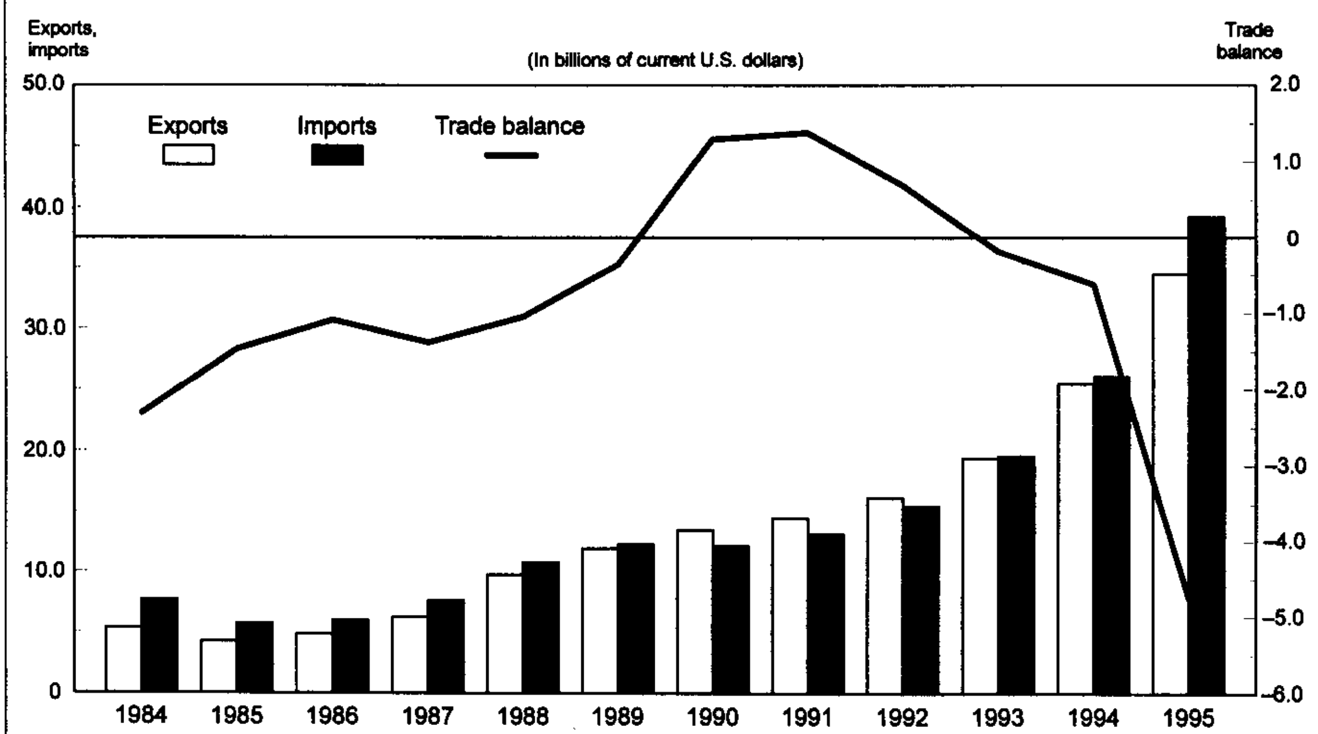
Manufacturing an integrated circuit starts with a blank silicon wafer. These wafers are either produced in-house or bought from a supplier. The major steps of wafer processing are film

Chart 3. **Employment and production indexes for semiconductor manufacturing, 1972–95**




SOURCES: BLS; Federal Reserve Board; and text references.

Chart 4. **U.S. semiconductor trade, 1984–95**




SOURCE: Electronic Industries Association, based on data from the U.S. Department of Commerce.

formation, impurity doping, lithography, and etching.

Processing starts with a film over the surface of the wafer to protect it from contaminants in the atmosphere. Next, the wafer is coated with a photosensitive material on which a pattern is drawn using lithographic techniques. Chemical etching transfers the pattern to the underlying silicon surface; certain impurities can be introduced selectively to achieve desired electrical properties. A complete integrated circuit contains many circuit layers, so that a wafer may require many cycles through these processing steps.

*Lithography techniques and shrinkage of chip geometry.* Lithography represents more than 35 percent of chip manufacturing costs. Optical lithography, the standard technique, draws circuit lines only half of a micron apart.[18] Such short distances between circuit lines allow chip designers to pack more components onto a single silicon crystal.

Larger wafers and chips with higher densities decrease unit costs and afford economies of scales by making possible more transistors per chip and per manufacturing step. In addition, higher densities allow more information processing per unit of time, thus yielding faster microprocessors and decreasing costs per function. These factors underlie productivity increases and the downward trend in prices of integrated circuits.

*Testing, assembly, and packaging.* The various circuits in the wafer need to be mechanically and electrically tested. In the assembly stage, the wafers are split into chips and each chip is fastened to a lead frame using a bonder. Molding and sealing equipment encapsulates the chips in ceramic or plastic packages.

*Integrated factory versus offshore production.* Currently, testing and packaging are labor-intensive activities relative to other processing steps. As mentioned earlier, this has favored low-cost chip assembly plants offshore, independent of wafer processing plants and R&D centers. However, the technical demands of manufacturing ever-smaller chips is leading to complex assembly and packaging steps amenable to further automation. This would reduce labor intensity and increase the proportion of higher-skilled labor in this part of the production process. In addition, submicron chips require more coordination both between research and production, and among the different manufacturing steps. This means that—at least for some segments of the industry—decentralized global production of a given batch of chips may not best use the expensive human and capital resources brought forth by these new requirements.

Over the long term, this could favor integrated plants[19] with high-skill workers involved in a continuum of tasks, from modeling and simulation, to processing and assembly. This is likely to diminish the leverage of offshore contract manufacturers using low-skill, low-cost labor. Under this scenario, automation and advanced manufacturing would benefit U. S. semiconductor employment by transforming its jobs into ones less likely to be shifted elsewhere. Until now, this possibility has received little attention by most industry observers.

This is not to say that outsourcing arrangements are likely to disappear, given that contract manufacturing has a flexibility element useful in the presence of sudden changes in the market. In addition, the strategic importance of offshore plants as stepping stones into emerging markets, such as China and Eastern Europe, is not likely to diminish.

## Research developments

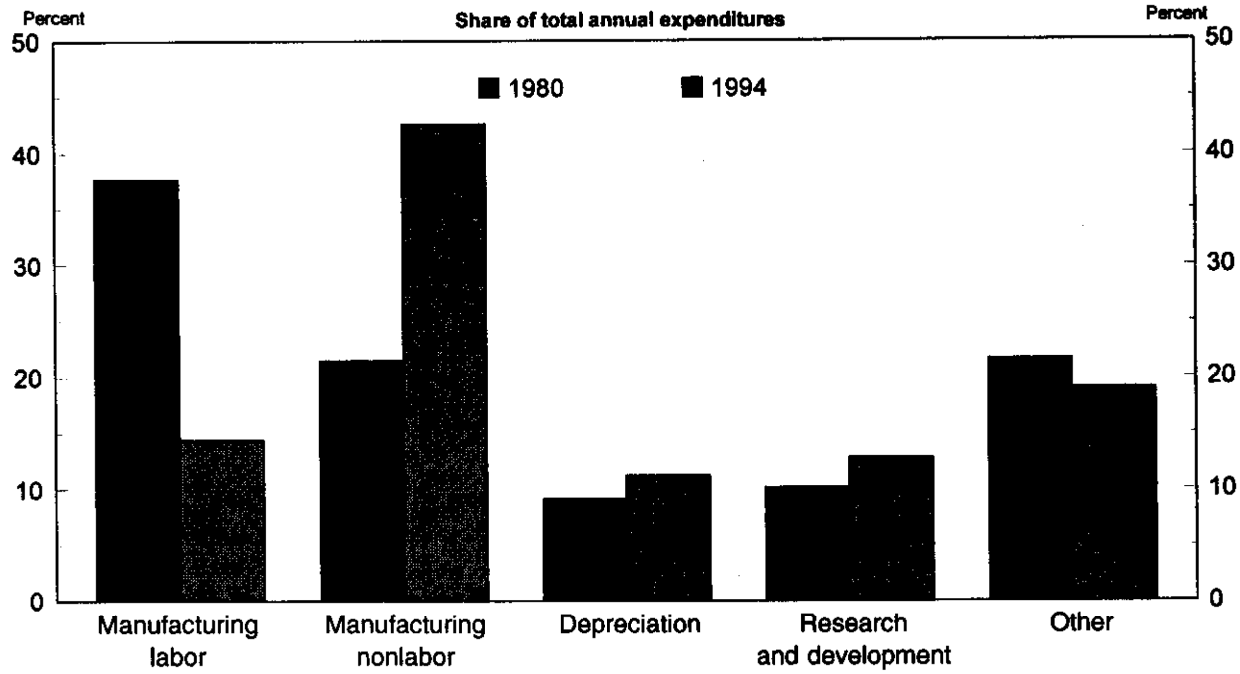
The objectives of current research are faster microprocessors without increased power consumption, and memory chips with higher capacities. The two basic research strategies are miniaturization of the chip with higher transistor densities (as detailed above) and the use of new electronic materials. The latter include compound semiconductors such as silicon-germanium and gallium-arsenide chips. Either research strategy requires complementary development of labor skills.

Current memory chip technology has a capacity of 16 megabits (16 million bits).[20] A 64-megabit chip is set for production by an international joint venture. Researchers are well along the way to developing a 256-megabit chip and the semiconductor industry's National Technology Road-map[21] has set ambitious targets for the next generation of IC's. This agenda calls for DRAM's with circuit lines less than a tenth of a micron apart and 64 gigabits per chip (64 billion bits) to be in production by the year 2010.

Higher component densities not only increase the amount of information a chip can hold, they also facilitate the integration of additional circuits for new features, such as multimedia capabilities. Multimedia chips, able to work with data, audio, sound, and images for 3D graphics and video applications, are becoming available for the home PC market.[22] For example, chips with graphics circuitry have already been produced for video-game machines. There are also plans to put digital cellular telephone functions in a custom chip and develop a computer workstation based on a chip with built-in video compression and networking capabilities.[23]

Product development projects at private companies, together with research universities and major Federal R&D agencies serve as skill-development sources. Semiconductor Industry Association data show that U. S. firms employ 60 percent of semiconductor workers in manufacturing activities and about 20 percent in R&D tasks.[24] Public company reports show R&D employment to be as high as 30 percent of worldwide operations employment. Smaller high-tech companies that aim at niche IC markets are likely to have an even larger proportion of employees in R&D functions, including techni-

Chart 5. Cost structure of the U.S. semiconductor industry, 1980 and 1994




SOURCE: Semiconductor Industry Association.

cians and engineers who perform both production and research tasks.[25]

Current Employment Statistics data show that semiconductor production workers have fluctuated in a narrow range between 40 percent and 50 percent of total employment since 1972. Production positions include manufacturing operators and maintenance technicians. Many of these positions are high-skilled, given the degree of development of semiconductor manufacturing techniques. This has brought local shortages of skilled semiconductor labor, especially entry-level positions. The situation has prompted the training departments of some chip firms to team with local community colleges to develop specialized semiconductor programs for production jobs.[26]

## Costs and earnings

Even though semiconductor employment increased 5 percent from 1980 to 1995, the share of labor-related manufacturing costs actually decreased over the same period,[27] due to the combined effect of increases in productivity and increases in capital expenditures relative to total expenditures. In fact, nonlabor manufacturing costs have increased significantly. (See chart 5.) The increase in these production costs and depreciation expenses is associated with investing in expensive, complex equipment with high operating and maintenance costs. In 1994, the industry spent $9 billion in new property, plant, and equipment. Between 15 and 20 percent of sales revenue is spent annually by U. S. semiconductor firms on capital expenditures. Two-thirds of these expenditures go to wafer fabrication equipment.

R&D costs have averaged an annual growth rate of 16 percent since 1978. Increasing R&D costs is necessary because of the rapid rate of technological change. Semiconductor R&D expenditure was $4.7 billion or 10.6 percent of sales in 1994. Research expenses for semiconductor firms are higher ,as a share of revenues than those for overall manufacturing, computer communications, computer manufacturing, general electronics, pharmaceuticals—in fact, higher than any industry except software services.

Although *total* costs are high, capital expenditures and R&D outlays aimed at higher chip densities have paid off in terms of lower *unit* costs, lower labor manufacturing costs, and higher sales per employee.[28] This, in turn, has afforded lower prices. Semiconductor unit production costs decline as production experience, measured by cumulative output, increases. According to one estimate,[29] unit production costs in this industry fall by 20 percent every time cumulative output doubles. Correspondingly, prices of integrated circuits, including microprocessors and memory chips, have come down considerably. (See chart 6.) Attempts to increase market share and to prevent entry of competitors are two other factors driving the decline of computer chip prices.

Increases in productivity have not only decreased unit costs and prices but have also sustained above-average worker compensation. Within the United States, average hourly earnings for production workers in the semiconductor industry were $14.59 in 1995, 18 percent above the average for all manufacturing.[30] This reflects, in part, higher skill and value added associated with the capital-intensive processing steps and R&D activities performed by U. S. semiconductor workers.

Furthermore, according to the Semiconductor Industry Association, 50.6 percent of worldwide employment of U. S.-based merchant semiconductor firms was located in North America in 1994, but 70.6 percent of their worldwide labor expense was incurred there. This implies that more of the industry's high value added functions took place in the United States.

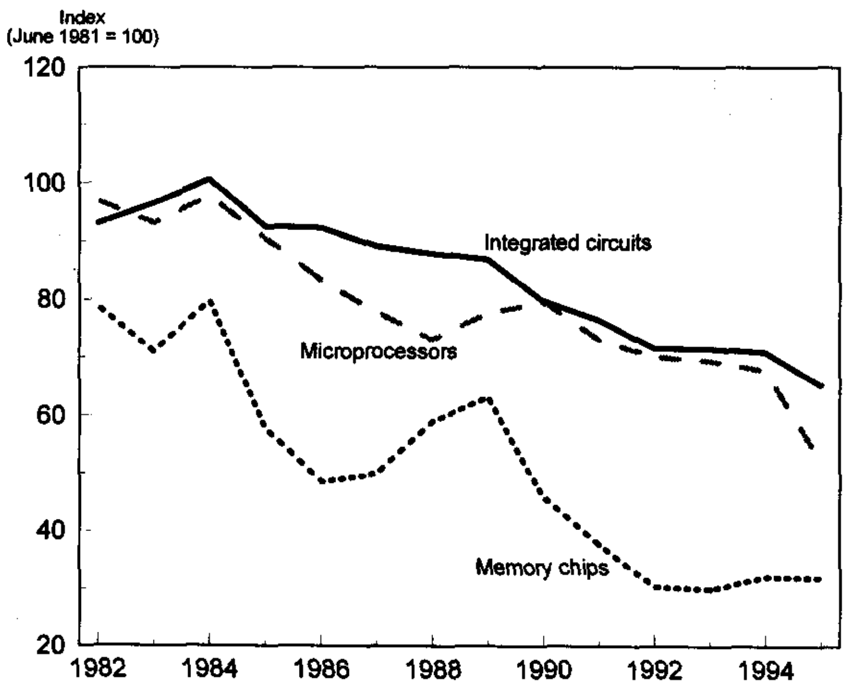
## Outlook

The major factors affecting employment in semiconductors have been cyclical downturns in the industry, technology breakthroughs, and secular demand growth. The balance between technology and costs, and how the industry responds to cyclical change and long-term demand will determine employment growth in semiconductors for years to come.

*Recent history.* From late 1995 through early 1996, the semiconductor industry found itself in a softening market. Slower orders stemming from increased chip inventories in the personal computer end-use market prompted semiconductor companies and stock analysts to reduce revenue expectations for 1996. This sparked cost containment efforts—from reduced capital spending plans to hiring freezes. In fact, the semiconductor book-to-bill ratio (new orders divided by billings or shipments) declined to its lowest levels since the mid-eighties in the first quarter of 1996. Historically, employment growth in the industry cannot be sustained with a ratio below one, where it has been since the beginning of the year. This suggests that semiconductor employment growth is likely to plateau in the short run until the effects of this slowdown work itself out. Some firms already have announced layoffs affecting worldwide operations.[31]

*The long view.* Current problems facing the semiconductor industry—stemming from slow chip orders from PC makers—are likely to be temporary, and mostly confined to the memory chip segment of the industry. Semiconductors now have a substantial presence in new high-margin applications such as the communications market with advanced chips for high-speed modems for fax and Internet access. Furthermore, the domestic slowdown is buffered by exports and global production sites.

Chart 6. **Semiconductor prices, 1982–95**




NOTE: Memory chip index is for MOS memory.
SOURCE: Producer Price Index program, Bureau of Labor Statistics.

Worldwide semiconductor sales are expected to grow at rates of 6 percent to 19 percent annually through the end of the century.[32] This growth is expected to be pulled by two technology-related factors: first, increased demand for DRAMs and microprocessors for personal computers and telecommunications equipment, including multimedia applications. Factors behind this growth include the transition from analog to digital electronic applications, and the trend from wired to wireless communications. The second factor is the increase in the percentage of semiconductor content in a host of household electronic products, automobile electronic gear, and industrial and medical devices.

Continued advances in chip manufacturing and the global nature of semiconductor production and trade posit several scenarios for human resources needs. Even if the rate of periodic technology advances slows at some point early in the next century—after physical limits of miniaturization of chips become harder and more expensive to overcome—there will be long-term labor implications.

As technology advances, U. S. semiconductor workers increasingly are performing knowledge-based tasks, whether R&D, chip design, or production. Automated assembly processes and the integrated semiconductor factory could change the economics of offshore chip assembly. Nevertheless, the share of offshore employment has changed little in the last 15 years, in spite of a host of technology developments (including automated processes), trade deficits, and higher domestic labor costs.

On the other hand, the high cost of semiconductor manufacturing facilities makes small manufacturers more vulnerable to the overall decline in chip prices. Firms unable to invest continually to either develop advanced chips or to set up efficient manufacturing for high-volume production are likely to either consolidate or exit the business altogether. So far, this has not been a widespread event.

Semiconductor companies faced difficulties in meeting the surge in demand for memory chips and microprocessors during 1995, spurring plans to increase chip capacity and causing shortages of silicon wafers still affecting the market.[33] Expansion plans to overseas markets include new plants in Southeast Asia and China. In the United States alone, more than 10 major companies are building or planning new fabrication plants and chip design centers over the next 2 years.[34] This bodes well for continued job growth. However, the current slowdown has prompted delays (but no cancellations, as of mid-1996) of some firm's expansion plans.

Even new foreign locations are not likely to come at the expense of U. S. semiconductor workers. The size of the emerging semiconductor markets is likely to call for a larger global labor pool, in the long term, as opposed to a mere shift of production sites. In addition, new generation chips are likely to be developed and market-tested in advanced markets, especially the United States.

The balance of these factors points to softer job growth during 1996, with a brighter outlook over the long term. From the technology or product supply side, the development of faster and more versatile computer chips is likely to demand high-skill U. S. labor, even if advances in semiconductor manufacturing techniques and automation continue to increase labor productivity. In addition, growth in demand for memory chips and microprocessors, the largest semiconductor segments, is going to be pulled by a projected long-term increase in the use of desktop and laptop computers, and electronic communications products worldwide. Foreign semiconductor firms, for their part, are being lured here by the fact that the United States sports the largest advanced consumer market and a sophisticated labor force. The convergence of these factors are likely to sustain U. S. semiconductor job growth and above-average worker earnings well into the next century. □

## Footnotes

[1] An *electronic circuit* is a closed path of devices that produce and manage electricity (a current of electrons). It has three basic components. *Active components* (such as transistors and diodes) produce and transfer electricity. *Passive components* (such as capacitors, resistors, and inductors) direct, transform, or store electricity. Finally, a *printed circuit board* is the physical structure where all the components are mounted and where the electrical interconnection of the components is established.

[2] A bit or binary digit can take a value of either 0 or 1, representing on/off electrical switches. Memory capacity is measured in kilobits ($2^{10}$=1,024 bits), megabits ($2^{20}$ bits, or about a million bits), and gigabits ($2^{40}$ bits, or about a billion bits).

[3] Memory chips—read-only memory (ROM) and random access memory (RAM) chips—contain the internal memory of a computer. ROM is permanent memory whereas RAM is temporary. DRAM's are Dynamic Random Access Memory chips.

[4] For an analysis of employment in the computer industry, see Jacqueline Warnke, "Computer manufacturing: change and competition," pages 18–29, this issue.

[5] *1995 Annual Databook* (San Jose, CA, Semiconductor Industry Association, 1995. See also www.semichips.org). Data for the North American market exclude foreign-owned companies. Most of the plants included are in the United States, with a few plants in Canada and Mexico.

[6] Southeast Asia is specially strong in chip foundries.

[7] Advanced Micro Devices, for example, acquired NextGen Inc. in early 1996. The companies expect to better compete against Intel, a leader in PCs microprocessors.

[8] In fact, Samsung Electronics Co., of South Korea is the world largest DRAM maker in terms of 1994 sales, followed by Hitachi, NEC, and Toshiba of Japan. Texas Instruments, IBM, and Micron Technology Inc. are the largest U. S. firms in this market. See "Micron Technology survives and then some," *The New York Times*, Sept. 5, 1995, p. D1, "Bad times are just a memory for DRAM makers," *The Wall Street Journal*, Aug. 28, 1995, p. B4, and "Chips," *Business Week*, Aug. 28, 1995.

[9] Products in the communications market include telephone equipment, radio paging and wireless data systems, land mobile products, and cellular and personal communications systems. The industrial sector includes control and measuring equipment and energy storage products. Consumer products include pocket calculators, audio, video, and other home appliances.

[10] *Employment and Wages, Annual Averages, 1994*, Bulletin 2467 (Bureau of Labor Statistics, October 1995.)

[11] See "Silicon forest," *The Wall Street Journal*, Aug. 4, 1995, pp. A1, A5. Virginia could become a regional center for semiconductor production and employment if recent plant building announcements materialize in the next few years. See "A dream of silicon Virginia," *The Washington Post*, Aug. 14, 1995.

[12] "As computer titans focus on design, smaller firms undertake actual output," *The Wall Street Journal*, Sept. 11, 1995, p. B5A; "Silicon Valley manufacturers are seen as beneficiaries of the dollar's rise," *The Wall Street Journal*, Sept. 12, 1995, p. A2.

[13] Sales data from Semiconductor Industry Association. The Federal Reserve Board's Industrial Production Index (seasonally adjusted) for semi-

conductor and related products was 276.3 in 1995 (1987=100). This index includes production in all four-digit SIC codes under 367, except 3671. Production estimates from *U. S. Markets Review: Industry Focus, Fall-Winter 1994–95* (Lexington, MA, DRI/McGraw-Hill, November 1994.)

[14] For a historical perspective, see *Issues confronting the semiconductor industry*, Hearings before the Subcommittee on Technology and the Law, Committee on the Judiciary, U. S. Senate, 101st Congress, 1987. These hearings considered amendments to the 1984 Semiconductor Chip Protection Act. See also *A Strategic Industry at Risk.* (National Advisory Committee on Semiconductors, 1990). The trade agreement is up for renewal in July 1996, but Japanese chip firms want to end the accord. The Japanese argument is summarized in *Mission accomplished* (February 1996), Electronics Industry Association of Japan (www.eiaj.org). See also *The Wall Street Journal*, Nov. 3, 1995, p. A10; and *Investor's Business Daily*, November 3, 1995, p. A34.

[15] Electronic Industries Association, based on U.S. Department of Commerce data.

[16] L. Davis, *U. S. jobs supported by goods and services exports, 1983–92.* (U. S. Department of Commerce, Economics and Statistics Administration, Office of the Chief Economist, May 1995.) Data are in full-time equivalents.

[17] Sources: *McGraw Hill Encyclopedia of Science and Technology*, Les Freed, *The history of computers* (Emeryville, CA , Ziff-Davis Press, 1995), *The U. S. semiconductor wafer processing equipment market* (U.S. Department of Commerce, International Trade Administration, 1992), and *Global Competitiveness of U. S. Advanced Technology Manufacturing Industries: Semiconductor Manufacturing and Testing Equipment* (U.S. International Trade Commission, September 1991.)

[18] A micron is a millionth of a meter. The diameter of the human hair is about 200 microns.

[19] For a background on the future integrated chip plant see *National Technology Roadmap* (San Jose, CA, Semiconductor Industry Association, 1994.)

[20] See footnote 2.

[21] See reference in footnote 19.

[22] For employment generated by the home computer market, see Laura Freeman, "Job creation and the emerging home computer market," pp. 46–56, in this issue.

[23] "LSI Logic unveils process to increase transistors on semiconductor chips," *The Wall Street Journal*, Sept. 18, 1995, p. B9; "Intel puts chip under Pentium brand, meaning some won't reap its benefits," *The Wall Street Journal*, Sept. 20, 1995, p. B8; "Intel to trot out next chip generation; high speed and low price are surprise," *The Wall Street Journal*, Nov. 1, 1995, p. B6; "Sun Microsystems Inc. to unveil computers based on new chip," *The Wall Street Journal*, Nov. 7, 1995, p. B2.

[24] See reference in footnote 5.

[25] Semiconductors and microelectronics also support employment in R&D and engineering *services* related to these manufacturing activities. For employment in engineering services, see William C. Goodman, "The software and engineering industries: threatened by technological change?" pp. 37–45, in this issue.

[26] Solid State Technology newsletter, *Headlines*, 4-18-96, http://www.solid-state.com.

[27] Based on Semiconductor Industry Association data, which exclude foreign-based U. S. plants.

[28] Sales per employee have more than tripled, from $38,000 per employee to $147,000 per employee between 1978–93 (based on BLS and Bureau of the Census data). There are no productivity data for SIC 3674 published by BLS.

[29] D. A. Irwin and P. J. Klenow, "Learning-by-doing spillovers in the semiconductor industry," *Journal of Political Economy*, Vol. 102, No. 6, December 1994.

[30] The average hourly earnings data are from the Current Employment Statistics program and cover all plants located in the United States, including foreign-owned establishments.

[31] Company press releases: *National Semiconductor* (4-2-96); and *Cirrus Logic* (3-19-96).

[32] *1996 Spring Forecast, World Semiconductor Trade Statistics* (San Jose, CA, Semiconductor Industry Association, 1996)

[33] "Running wafer-thin," *Business Week*, Mar. 25, 1996; and public company reports.

[34] Some of these companies are: Analog Devices, VLSI Technology, LSI Logic Corp., Motorola, IBM/Toshiba, Intel, Texas Instruments/Hitachi, Hyundai Electronics, Samsung Semiconductor, Mitsubishi Semiconductor America Inc., and Sumitomo Sitix Corp. See "In the hot world of chips, tradition melts," *The Wall Street Journal*, Oct. 30, 1995, p. B4; "IBM, Toshiba Corp. plan $1.2 billion plant for computer chips in Manassas, VA," *The Wall Street Journal*, Aug. 8, 1995, pp. A2, A14; "Motorola to build a chip plant in (Richmond) Virginia," *The New York Times*, Sept. 8, 1995, p. D2; "Texas Instruments hikes 1995 growth forecast," *Electronic News*, June 26, 1995; "Hyundai Electronics' semiconductor fabrication plant in Eugene, Oregon," *Electronic News*, May 29, 1995; and "More capacity expansions slated," *Electronic News*, May 22, 1995.