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# Semiconductors

JEFFREY T. MACHER

*Georgetown University*

DAVID C. MOWERY

*University of California, Berkeley*

ALBERTO DI MININ

*Scuola Superiore Sant'Anna, Pisa, Italy*

### INTRODUCTION

The determinants, patterns, and consequences of globalization of the innovative activities of U.S. high-technology firms are the subject of a large empirical literature. Among the central questions addressed within this research is the extent to which international flows of research and development (R&D) investment and the offshore movement of other forms of innovative activity are linked with U.S. firms' foreign investments in manufacturing and related activities. A second important issue concerns measurement of the internationalization of firms' innovative activities—firm-level R&D investment data often do not capture developments within individual technological or industrial fields, and R&D data may provide little information on important aspects of the internationalization of firms' innovation-related activities. Partly because of the imperfections of these data, analyses of the globalization of innovative activity rarely consider developments within individual industries.

This chapter addresses these challenges in an examination of trends in the globalization of innovation-related activities in a single industry—semiconductors. We consider several measures of innovative activity within this industry, including R&D investment, technology-development alliances, and patenting. As is often the case in empirical work, the insights from this approach are obtained at some cost, confining our analysis to a relatively short time period and limiting our discussion of trends in the globalization of non-U.S. semiconductor firms' innovation-related activities. In addition, the data themselves represent imperfect proxies for the actual phenomena that we wish to examine. The different innovation-related indicators also do not aggregate in a straightforward

way, which complicates efforts to develop strong conclusions concerning the consequences of these trends. Remarkably, after more than 30 years of intensive study of the internationalization of R&D and other innovation-related activities in the semiconductor industry, the data on these trends remain fragmented and limited in their coverage. Nevertheless, the results of our analysis highlight several distinctive trends in the globalization of innovation-related activities in this industry:

1. The share of industry-funded R&D investment devoted to offshore R&D by U.S. firms in “electronics components” manufacturing (an industry category that includes semiconductors, along with several other electronics product segments) grew only modestly during 1985-2001.

2. The number of technology-development alliances in the global semiconductor industry declined during the 1990s, although alliances among foreign firms appear to have grown more substantially than alliances among U.S. semiconductor firms during this period.

3. Process-technology R&D remains “homebound” in the home countries of U.S. and non-U.S. semiconductor firms, based on trends in the siting of “development” fabrication facilities (“fabs”).

4. The patenting activity of large U.S. integrated semiconductor firms (those that both design and manufacture their products) remains predominantly “homebound,” with little increase in offshore inventive activity in their patents during the period 1991-2003.

5. Patenting by European, Japanese, and Taiwanese semiconductor firms is similarly dominated by domestic inventive activity and this dominance by “home country” inventive activity appears to have increased slightly during the period 1996-2003.

6. The patenting activity of U.S. “fabless” semiconductor firms, which design and market but do not manufacture their products, indicates modest growth in offshore inventive activity during the period 1991-2003.

7. Although the vast majority of inventive activity undertaken by non-U.S. firms remains homebound, the United States is the predominant location for offshore inventive activity of all but Canadian semiconductor firms.

8. There is little evidence that the changing international structure of U.S. semiconductor firms’ innovation-related activities has had negative consequences for engineering employment in the U.S. semiconductor industry, reflecting the limited offshore movement of innovation-related activities documented by these indicators.

Taken as a whole, our findings underscore the importance of a broad view of the array of activities that contribute to innovation in the semiconductor industry. These results also highlight the influence of growing vertical specialization on the globalization of innovation in this industry. Interestingly, the expanded offshore

investment by U.S. semiconductor firms in production capacity does not appear to have influenced movement of their R&D activities to non-U.S. locations. Instead, the most important influence on the expanded offshore inventive activities of a subset of U.S. semiconductor firms (the fabless firms) may be the emergence of new segments of market demand that are concentrated in Southeast Asia. But even within the fabless segment of the U.S. semiconductor industry, the contributions of “offshore” innovation-related activities are modest thus far.

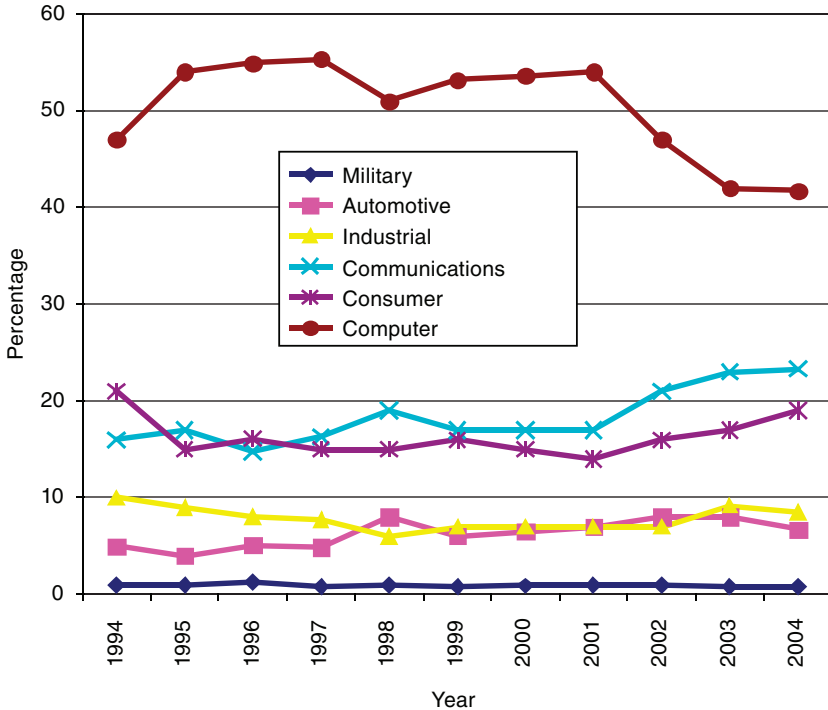
### **STRUCTURAL CHANGE IN THE GLOBAL SEMICONDUCTOR INDUSTRY**

The global semiconductor industry experienced significant structural change during the 1990s. The market for semiconductor components shifted from one dominated by personal computers (PCs) to a more diverse array of heterogeneous niches associated with the Internet and wireless communications applications. The integrated device manufacturers (IDMs) that both design and manufacture semiconductor components no longer dominate industry production and innovation; instead, a vertically integrated industry segment coexists with a vertically specialized segment. IDMs compete and often collaborate with firms that specialize in either design and marketing (fabless firms) or manufacturing (foundries). As is the case in other high-technology industries, semiconductor-related market demand and technical expertise are growing in geographic regions that formerly accounted for smaller shares of global demand for semiconductor components (e.g., Malaysia, Taiwan, Singapore, China).

#### **The Decline of the PC and Emergence of New Component Markets**

The market for end-use semiconductor components during the late 1990s and early 2000s experienced a gradual shift away from one dominated by computer applications (especially PCs) to a more fragmented market in which wireless communications and other non-PC consumer products are more significant (Linden et al., 2004). Figure 1 depicts the shares of chip consumption accounted for by different end-use markets during the period 1994-2004. Computer applications still represent the predominant end-use market for semiconductor components, but most industry observers agree that non-computer (i.e., communications and consumer product) markets for semiconductor components will grow more rapidly during the next decade.

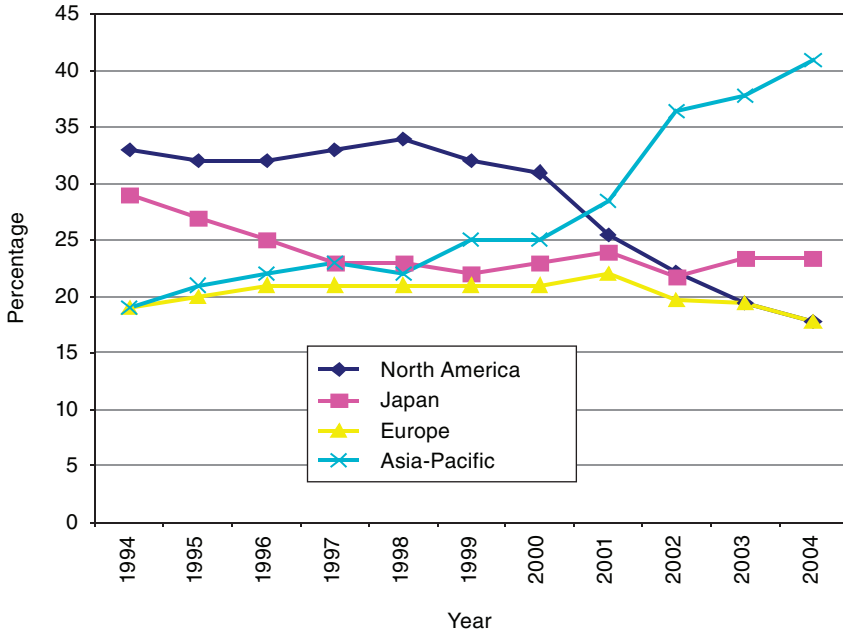
Differences between PC and non-PC markets for semiconductor components mean that this shift in consumption patterns has important implications for the organization of innovative activities in the semiconductor industry. The PC market is characterized by an entrenched architectural standard (the so-called Wintel standard), with well-defined and stable interfaces among semiconductor components and PC components. This stable architectural standard contrasts with the



**FIGURE 1** Semiconductor end-use markets by application, 1994-2004. SOURCE: Integrated Circuit Engineering (ICE) and IC Insights.

situation in many non-PC markets, where new products require more extensive “design-in” efforts on the part of component suppliers, and the interfaces governing the design and compatibility of components for these products can change significantly through successive product generations. No single product dominates semiconductor end-use demand in these applications—another contrast with PC component markets. As a result, production runs of new component designs are likely to be smaller and the cost savings through production-based learning will decline in significance. Smaller production runs also mean that new semiconductor production capacity, the costs of which continue to rise, must become more flexible and capable of producing a wider variety of component designs.

The relative decline of the PC market for semiconductors has important implications for the geographic location of demand for semiconductor components. The PC market has been dominated by designs developed in the United States and by an architecture that was largely under the control of U.S. firms. But designers



**FIGURE 2** Semiconductor end-use markets by geographic region, 1994-2004. SOURCE: Integrated Circuit Engineering (ICE) and IC Insights.

and producers of the systems for which markets are growing more rapidly (e.g., wireless communications and consumer products) are more heavily concentrated in Southeast Asia, especially in Taiwan, Japan, and Singapore. Figure 2 illustrates the shifting geographic structure of demand during the period 1994-2004, highlighting declines in the share of global chip consumption accounted for by Japan and the United States and a corresponding rise in Southeast Asia's share.

Producers of these electronics systems often require that functionality be based on features in the semiconductor components incorporated in the products—so-called system-on-chip designs that are more complex and require more intensive interaction between system and chip designers (Ernst, 2005). Moreover, the number of new applications that use semiconductors has increased dramatically. The needs of an increasing variety of system providers mean that a one-size-fits-all model for semiconductor components is appropriate in only a limited number of cases. As a result, close interaction between designers of components and designers (as well as producers) of these more heterogeneous electronics systems is essential to product development. Proximity to system customers, more

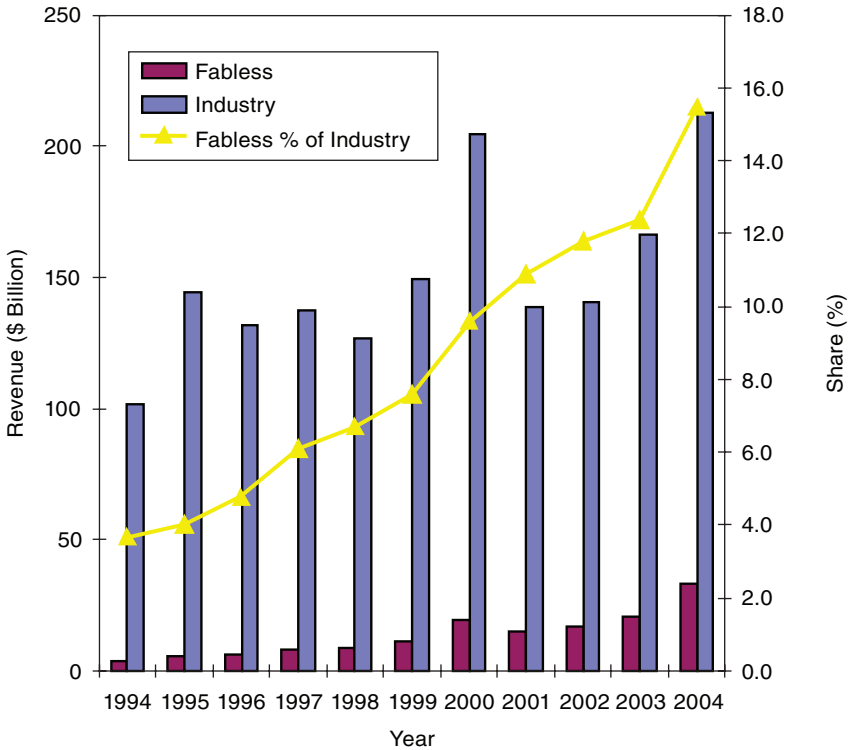
and more of whom are located in Southeast Asia, therefore is likely to grow in importance for developers of state-of-the-art semiconductor devices.

### **GROWTH OF VERTICAL SPECIALIZATION IN THE SEMICONDUCTOR INDUSTRY**

For the first two decades of the computer and semiconductor industries, large integrated producers such as AT&T and IBM designed their own solid-state components, manufactured the majority of the capital equipment used in the production of these components, and utilized internally produced components in the manufacture of electronic computer systems that were leased or sold to their customers (Braun and MacDonald, 1978). During the late 1950s, “merchant” manufacturers entered the U.S. semiconductor industry and gained market share at the expense of firms that produced both electronic systems and semiconductor components. Specialized producers of semiconductor manufacturing equipment began to appear by the early 1960s.

Since 1980, the interdependence between product design and process development has weakened in many semiconductor product segments (Macher et al., 1998). This shift has been associated with the entry of new types of firms that specialize in semiconductor component design or production. Hundreds of so-called fabless semiconductor firms that design and market semiconductor components have entered the global semiconductor industry since 1980. These firms rely on contract manufacturers (so-called foundries) for the production of their designs. Contract manufacturers include “pure-play foundries” that specialize in semiconductor manufacturing, as well as the foundry subsidiaries of established integrated device manufacturers (IDMs) seeking to fully utilize excess fabrication capacity. Fabless semiconductor firms serve a variety of fast-growing industries, especially computers and communications, by offering more innovative designs and shorter delivery times than integrated semiconductor firms. Fabless-firm revenues increased from slightly less than 4 percent of global industry revenues in 1994 to more than 15 percent by 2004 (Figure 3). The increasing demand for and variety of communications and consumer products (e.g., GPS systems, game controllers, appliances, automatic lighting) suggests that the demand for special-purpose functionality has also increased. The so-called embedded systems and software market represents a growing and increasingly important segment of the semiconductor industry, with its own vertically specialized market structure. Measuring the growth of this market segment, however, is hampered by a lack of data.

The growth of vertical specialization in the semiconductor industry reflects the influence of developments in markets and technology (Macher and Mowery, 2004). The expansion of markets for semiconductor devices enables vertically specialized semiconductor design and production firms to exploit economies of scale and specialization. Scale economies lower production costs, expanding



**FIGURE 3** Fabless and overall industry revenues, 1994-2004. SOURCE: Fabless Semiconductor Association (FSA) and Integrated Circuit Engineering (ICE).

the range of potential end-user applications for semiconductors and creating additional opportunities for entry by vertically specialized firms. The increasing capital requirements of semiconductor manufacturing provide another impetus to vertical specialization, since these higher fixed costs make it necessary to produce large volumes of semiconductor components in order to achieve lower unit costs. The design cycle for new semiconductor products also has become shorter and product life cycles more uncertain. As a result, it is more difficult to predict whether demand for a single product will fully utilize the capacity of a fabrication facility that is devoted exclusively to a particular product, increasing the risks of investing in such “dedicated” capacity. Since foundries tend to produce a wider product mix, they are less exposed to these risks.

At the same time, however, a number of large semiconductor firms (IDMs) still combine semiconductor device design and manufacture. The advantages of integrated management of design and manufacture are greatest in product lines

at the leading edge of semiconductor technology, especially in DRAMs (Macher, 2006). The relationship between the specialized foundry producers and the IDMs combines elements of cooperation and competition. For example, U.S. IDMs negotiated license agreements for the supply of product and process technologies to less-advanced semiconductor firms operating in Japan and South Korea during the 1970s, and U.S., Japanese, and European IDMs also supplied product and process technologies to Taiwanese and Singaporean foundry firms during the 1980s and 1990s. Many of these IDMs provided advanced process technologies to foundries in exchange for a guaranteed supply of semiconductor components. The development of a semiconductor intellectual property market also spurred growth in the number and importance of specialized product design firms (Linden and Somaya, 2003). Product and process licensing in the semiconductor industry has facilitated entry by both vertically specialized and integrated firms.

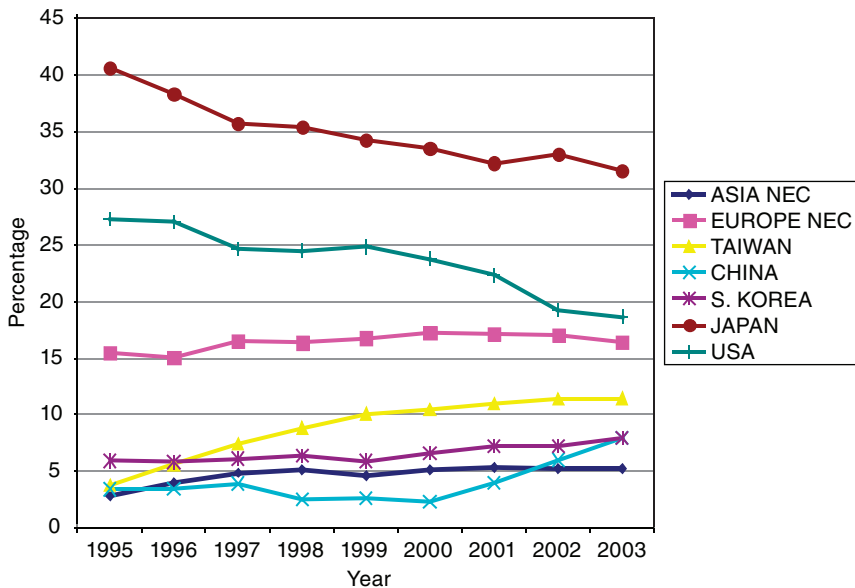
Increased vertical specialization in the semiconductor industry has been associated with the entry of new firms and geographic redistribution in production capacity. Figure 4 shows the regional distribution of fabrication capacity (measured in terms of wafer starts per month<sup>1</sup>) during the period 1995-2003. The North American and Japanese shares of global semiconductor production capacity fell significantly during the period, and the shares attributable to “Asia/Pacific” countries increased, reflecting capacity growth in China, Taiwan, South Korea, and Singapore. These Southeast Asian countries now collectively account for the largest regional share of global production capacity, and their share will continue to grow in the near future.

Figure 5 reclassifies manufacturing capacity by region of ownership rather than location for the period 1997-2003, revealing a slightly different pattern. The share of global manufacturing capacity owned by firms headquartered in Southeast Asian countries trails that of Japanese and North American producers. North American, Japanese, and (to a lesser extent) European semiconductor firms have shifted much of their production capacity to Southeast Asia since the mid-1990s and have entered joint ventures with Southeast Asian producers. Southeast Asian firms, on the other hand, have invested primarily within their home regions during this period.

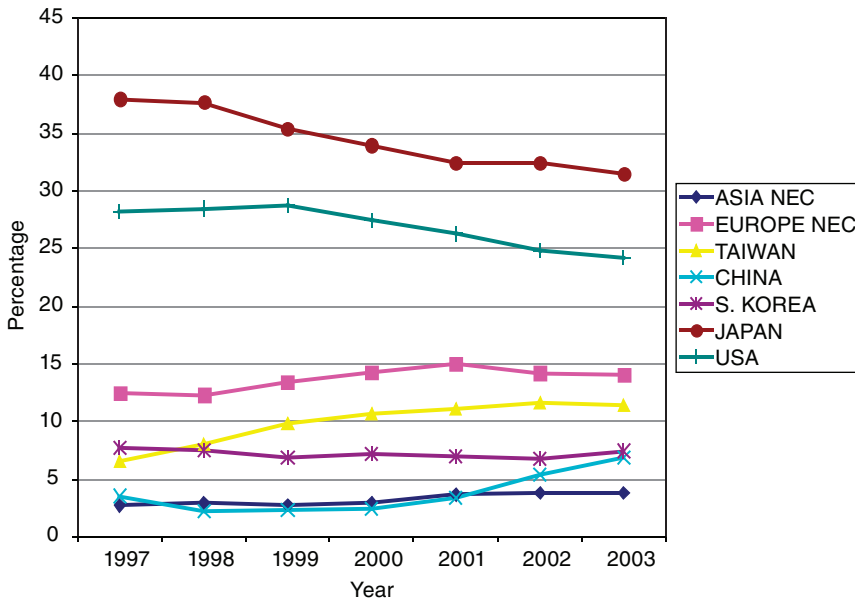
The growing concentration of manufacturing capacity in Southeast Asia is attributable in large part to the success of the foundry business model, which is reflected in foundry firms’ growing share of semiconductor-industry revenues (Figure 3). The most advanced foundries are located in Singapore and (especially) Taiwan. A few Taiwanese firms have opened foundries in the United

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<sup>1</sup>There are many possible measures of fab capacity, including the number of wafers processed over a given time period, the total wafer surface area that can be processed, the amount of installed processing equipment, and so on. Leachman and Leachman (2004) measure fabrication capacity as the estimated number of electrical functions that are produced by chip manufacturers, where a function is a memory bit or logic gate.



**FIGURE 4** Geographic location of semiconductor manufacturing capacity, 1995-2003.  
 SOURCE: Strategic Marketing Associates.



**FIGURE 5** Location of ownership of semiconductor manufacturing capacity, 1997-2003.  
 SOURCE: Strategic Marketing Associates.

States, and Taiwan's dominant position in the foundry industry faces competition from lower-cost production sites in other areas of Southeast Asia (particularly Malaysia and China) and elsewhere.

### U.S. DOMINANCE IN PRODUCT DESIGN

Although semiconductor manufacturing capacity now is widely distributed among mature and fast-growing regions within the global economy, semiconductor design activities, especially those associated with fabless firms, remain more concentrated. U.S. fabless semiconductor firms accounted for more than 60 percent of the value of orders received by the top four foundry firms (TSMC, UMC, Chartered, and SMIC) during the period 2000-2004.

Nonetheless, the growth of fabless firms in other countries is one indication of the widening geographic distribution of semiconductor-design activity and expertise. Table 1 indicates that several non-U.S. clusters of fabless firms have emerged in Israel, Canada, Taiwan, the United Kingdom, and South Korea. Although hundreds of fabless firms now operate in dozens of other countries, most of these firms are smaller than their U.S. counterparts.<sup>2</sup>

A number of factors have contributed to the success of U.S. firms in semiconductor design. Established regional high-technology clusters in areas such as Silicon Valley, Boston's Route 128, and Austin, Texas, attract large numbers of semiconductor designers. These clusters are located near universities and other research centers that produce new design techniques, design software, and engineering talent. The role of U.S. universities in developing new design software and chip architectures has long outstripped their function as a source of new manufacturing methods, in part because the cost of constantly re-equipping the necessary facilities exceeds the resources of most academic institutions.

Although we lack data to track these trends more systematically, most industry observers suggest that Southeast Asian countries account for a growing share of global semiconductor industry design activities (Brown and Linden, 2006a). As U.S. semiconductor firms, and especially fabless firms, seek to collaborate more closely with the systems firms that are located in Southeast Asia, a regional or local design presence is important. In addition, countries such as Taiwan and South Korea have developed product development expertise in digital consumer electronics and wireless communications, among other areas (Ernst, 2005). Off-shore design centers, particularly in China and India, may offer cost savings and comparable productivity in less-sophisticated design activities (Brown and Linden, 2006b). But most observers assess the semiconductor design capabilities of

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<sup>2</sup>The data in Table 1 that form the basis for this discussion include 640 fabless firms that are members of the Fabless Semiconductor Association (FSA) or nonmembers verified by the FSA. At least 300 other small fabless firms are thought to exist but have not been verified by the FSA.

**TABLE 1** Fabless Firms by Country of Location, 2002

Country	Fabless Firms	Non-U.S. City	Fabless Firms
United States	475	Tel Aviv, Israel	14
Canada	30	Ottawa, Canada	13
Israel	29	Hsinchu, Taiwan	13
Taiwan	22	Seoul, South Korea	9
United Kingdom	22	Taipei, Taiwan	8
South Korea	13	Toronto, Canada	8
Germany	8	Cambridge, England	4
France	6		
Japan	5		
Sweden	5		
Switzerland	4		
India	3		
Spain	3		
Others	15		
TOTAL	640		

SOURCE: Arensman (2003).

Chinese and Indian centers as lagging those of Canada, Israel, Taiwan, the United Kingdom, and the United States, as well as other industrial economies.

In summary, the structure of production activities in the global semiconductor industry has shifted from one dominated by vertical integration to a more complex structure that blends vertical specialization and vertical integration. Specialized design and manufacturing firms have entered the industry in large numbers, and the growth of foundry firms has been associated with a substantial shift in production capacity investment to Southeast Asia. Vertical specialization has facilitated the entry of new firms, many of which are located outside of the regions that were homes to established firms. But, thus far, increased vertical specialization in this industry appears to be associated with shifts in the location of production to a much greater extent than shifts in the location of product design and R&D activities.

## MEASURING GLOBALIZATION OF INNOVATION-RELATED ACTIVITIES IN SEMICONDUCTORS

### Indicators of Offshore Innovation-Related Activities

We use four indicators to examine trends in the offshore R&D activities of U.S. and non-U.S. other firms in the global semiconductor industry: (1) the share of industry-funded R&D expenditures supporting offshore R&D (available only for U.S. firms) during the period 1985-2001; (2) the number and location of development fabs established by U.S. and non-U.S. firms within the global

semiconductor industry during the period 1995-2003; (3) the number of international and domestic alliances formed by U.S. and non-U.S. semiconductor manufacturing firms during the period 1990-1999; and (4) the site of inventive activity resulting in U.S. patents issued to U.S. and non-U.S. semiconductor firms during the period 1994-2004. Each measure by itself provides an incomplete portrait of “globalization” of innovation-related activities within the global semiconductor industry, but taken together, they do shed light on the extent of globalization or nonglobalization of innovation within the industry.

### **Industry-Funded Offshore R&D Investment**

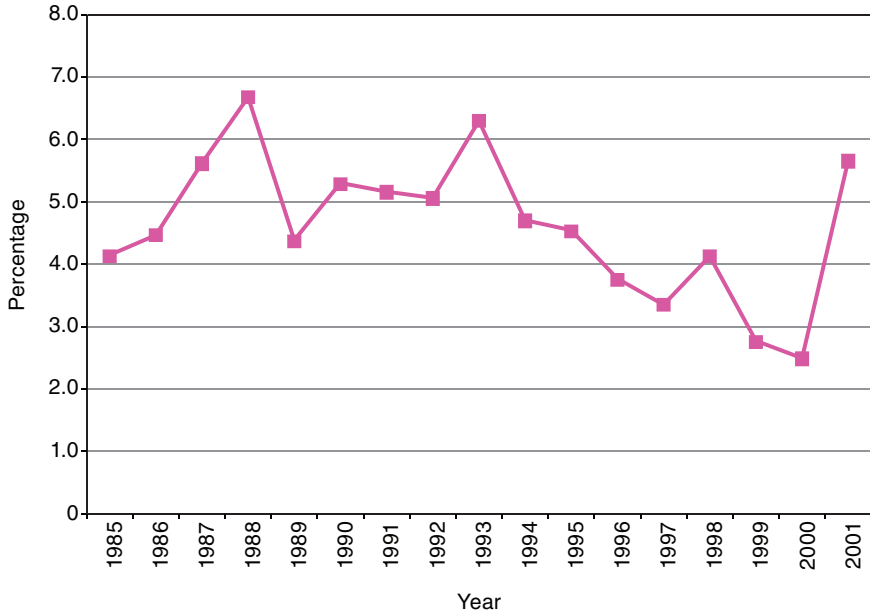
Figure 6 displays trends in offshore R&D investment (measured as a share of industry-funded R&D spending) by U.S. manufacturers of electronic components during the period 1985-2001. The data in the figure suggest minimal change in the share of offshore R&D within total industry-funded R&D, which drops to less than 3 percent by 2000 from its 1985 share of more than 4 percent.<sup>3</sup> The sharp increase during 2000-2001 in the offshore share of industry-funded R&D may or may not indicate a significant departure from this flat trend. In addition to the fact that this “reversal” covers only one year of data, the magnitude of the increase in reported offshore R&D during this period (more than doubling, from \$327 million in 2000 to \$852 million in 2001) suggests that a change in sample composition or other factors may be responsible, rather than a long-term shift in U.S. firms’ R&D investment behavior.

The industry-level R&D investment data compiled by the National Science Foundation (NSF) that are the source for Figure 6 have a number of well-known problems. Coverage by the NSF R&D survey of smaller firms (e.g., entrants), particularly for the longer time period depicted in Figure 6, is problematic since the NSF sample frame was not updated frequently during the 1980s and early 1990s. The “electronic components” product line for which these data were compiled by the NSF also includes a number of other products in addition to semiconductor components. Moreover, the definition of this and other product lines for which NSF collects R&D data have undergone some revisions during the period covered in Figure 6.

Even if the reported R&D data accurately summarize the trends in semiconductor-related offshore R&D investment, there is reason to suspect that the R&D investment data reported by semiconductor firms do not capture many of the activities that contribute to innovation in this industry. For example, R&D

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<sup>3</sup>We examined several sources of R&D data related to the globalization of innovation-related activity in the semiconductor industry. Most of these data, including publicly available information such as company Annual Reports and Form 10-Ks, did not yield time series that were consistent or covered most of the firms in the industry. We therefore narrowed our data sources to indicators that most effectively underscore trends in the offshore R&D activities of U.S. and other firms in the global semiconductor industry.



**FIGURE 6** Foreign R&D as percentage of industry-funded R&D (electronic components), 1985-2001. SOURCE: National Science Foundation (NSF).

investment data may not include process innovation or the “tweaking” that occurs within the production facilities of IDMs. As we note later in the chapter, much of the process innovation within foundries (few of which are operated by U.S.-headquartered firms) relies heavily on production-facility upgrades that may or may not be included in the R&D investments reported by firms. Design activities, especially those carried out by fabless firms, are another important source of innovations that may or may not be reported consistently as R&D investment.

These problems aside, the lack of a strong trend during the period 1985-2001 in reported offshore R&D investment is striking. This widely accepted measure of “globalization of innovation” indicates that U.S. semiconductor firms do not appear to be expanding this portion of their offshore innovation-related activities significantly, and the offshore portion of their self-financed R&D investment remains modest.

### Offshore Process-Development Facilities

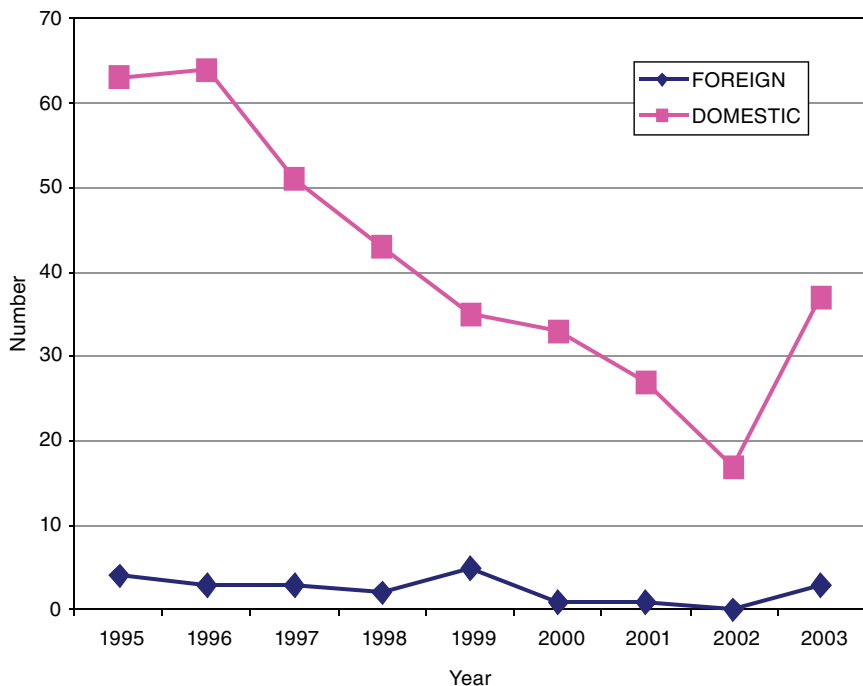
A second indicator of the offshore movement of semiconductor firms’ innovation-related activities is the location of their process-technology develop-

ment facilities during the period 1995-2003. These facilities are important sites for process innovation in the semiconductor industry, since they are used for the development and “debugging” of new manufacturing technologies (Appleyard et al., 2000; Hatch and Mowery, 1998). But this type of process innovation is irrelevant to innovation by fabless firms, whose designs are manufactured by foundries. Moreover, foundries rarely use development fabs. Rather than developing new manufacturing processes in dedicated R&D facilities and transferring these process technologies to full-volume production sites, foundries instead incrementally upgrade manufacturing processes within their full-volume production facilities. This approach enables the foundry firms to maintain stability and predictability in the evolution of the component designs that they produce for their customers. This indicator of the location of innovation-related activities therefore applies only to one segment of the global semiconductor industry—the IDM and systems firms.

The source for our data on the siting of semiconductor firms’ development facilities is Strategic Marketing Associates (SMA), a market research firm that tracks investment in semiconductor manufacturing facilities. The SMA data provide information on the home country for each firm in the dataset; years in operation and facility type (production, R&D, development, etc.) for each production facility; the technological sophistication (e.g., smallest linewidth of components produced), capacity, and size for each facility; and other information. Although the SMA database includes hundreds of public and private semiconductor entities, we exclude government and university-based facilities that are used solely for research and teaching purposes, research labs that possess production facilities for consulting purposes, and similar organizations.

The SMA data are collected through surveys. The development fabs that are included in the following discussion are used for the characterization of new (i.e., state-of-the-art) manufacturing processes and are typically much smaller (less than 5,000 wafer starts per month) than full-volume production facilities. The manufacturing facilities that we categorize as development fabs thus include facilities in which a variety of innovation-related activities are carried out. Nonetheless, these data are the only tabulation of which we are aware that can shed some light on the organization of the process R&D activities of IDMs and systems firms.

Figure 7 displays the number of “domestic” and “foreign” development fabs in operation during the period 1995-2003. Domestic development fabs are defined as those located in the home country of the semiconductor firm and foreign development fabs are located in a different host country. The overwhelming majority of development fabs are located in semiconductor firms’ home countries. The “homebound” nature of process-technology development appears to reflect the demanding technical requirements of this activity, the need for close coordination between product design and process-technology development, the need for an iterative approach to the introduction of new manufacturing processes, and the



**FIGURE 7** Foreign and domestic development fabs in operation, 1995-2003. SOURCE: Strategic Marketing Associates.

importance of close coordination between the process-technology development activities and commercial-scale production operations of the firm. Other empirical work has corroborated the importance of co-location of manufacturing and process-technology development activities (Hatch and Mowery, 1998; Macher and Mowery, 2003).

Figure 7 also reveals a decline in the number of development fabs during the period 1995-2003. This trend is another reflection of the structural change in the semiconductor industry that we discussed earlier. A growing share of global production capacity in the semiconductor industry now is accounted for by foundries, which typically do not use development fabs. Even within the IDM/systems-firm segment of the industry, the high capital costs of new commercial-volume production facilities (now more than \$3 billion) have raised the minimum efficient scale of production fabs and appear to have contributed to some shrinkage in the number of new commercial-volume facilities.

Table 2 and Figure 8 provide additional detail on the location of development fabs. Table 2 disaggregates foreign development facilities by country of location and country of ownership. The United Kingdom, Germany, and the United

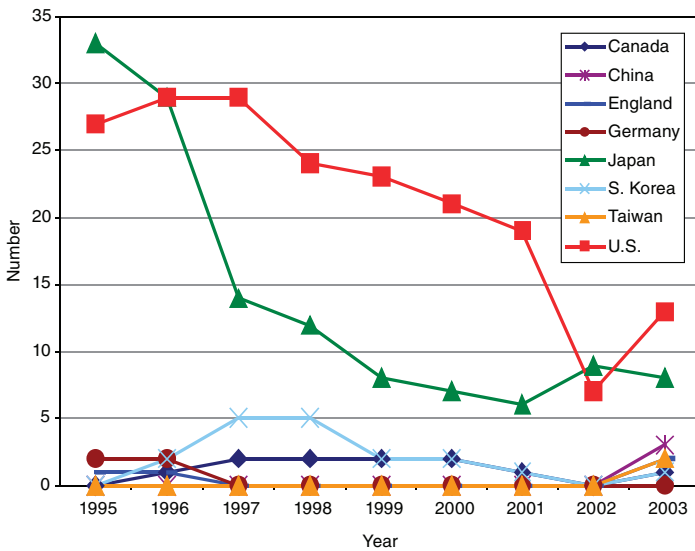
**TABLE 2** Foreign Development Facilities in Operation, 1995-2003

Country of Location	1995	1996	1997	1998	1999	2000	2001	2002	2003
Canada	0	0	0	0	0	0	0	0	0
United Kingdom	2	2	1	0	0	0	0	0	0
France	0	0	0	1	1	0	0	0	0
Germany	0	0	2	1	1	1	1	0	2
Italy	0	0	0	0	1	0	0	0	0
Japan	1	0	0	0	1	0	0	0	0
Netherlands	0	0	0	0	0	0	0	0	0
Taiwan	0	0	0	0	0	0	0	0	1
United States	1	1	0	0	0	0	0	0	0

Country of Ownership	1995	1996	1997	1998	1999	2000	2001	2002	2003
Canada	0	1	0	0	0	0	0	0	0
United Kingdom	0	0	0	0	0	0	0	0	0
France	0	0	0	0	0	0	0	0	0
Germany	0	0	2	1	1	1	1	0	2
Italy	0	0	0	0	1	0	0	0	0
Japan	1	0	0	0	0	0	0	0	1
Netherlands	2	2	1	0	0	0	0	0	0
Taiwan	0	0	0	0	0	0	0	0	0
United States	1	0	0	1	3	0	0	0	0

SOURCE: Strategic Marketing Associates.



**FIGURE 8** Geographic location of domestic development fabs, 1995-2003. SOURCE: Strategic Marketing Associates.

States are the leading locations for foreign-owned development fabs (keeping in mind that these represent a small fraction of total development-fab capacity). Semiconductor firms headquartered in Germany, the Netherlands, and the United States have a greater tendency to invest in foreign development fabs than do semiconductor firms based in other countries. Although interesting, the very small number of observations on offshore development fabs make it difficult to conduct additional analyses of the reasons for these differences.

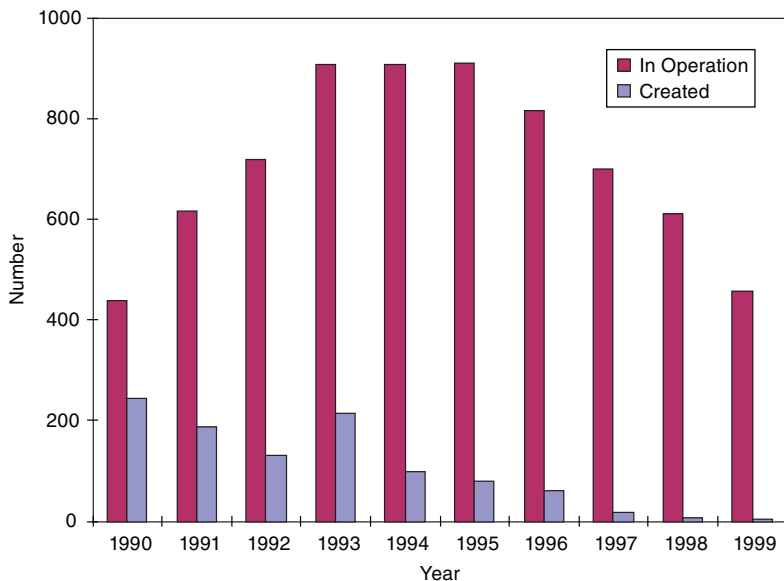
Figure 8 disaggregates “domestic” development facilities by country of location (as in Table 2, these data refer to the stock of development fabs in operation). Japanese and U.S. semiconductor firms operate the majority of domestic development fabs, and those operated by U.S. semiconductor firms outnumber Japanese “homebound” development fabs during this period. Consistent with Figure 7, the number of domestic development fabs owned by Japanese and U.S. firms fell during the period 1995-2003. Also notable within these data is the lack of Taiwanese-owned domestic production facilities, reflecting the fact that the Taiwanese semiconductor industry is dominated by foundries.

### **International Technology-Development Alliances**

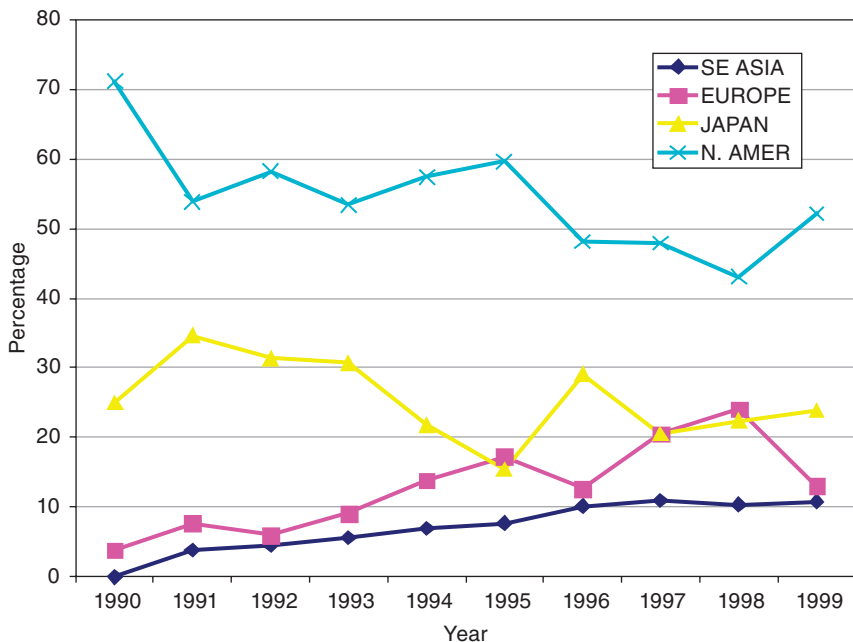
Our third indicator of globalization of innovation-related activities is the innovation-related alliances formed by U.S. and non-U.S. semiconductor firms during the period 1990-1999. The data that we use to track alliances in this industry cover both domestic and international alliances and were obtained from the *Profiles of IC Manufacturers and Suppliers* published by Integrated Circuit Engineering (ICE), a semiconductor industry market research firm.

Alliances in the ICE database include a number of different activities related to innovation and technology development in semiconductors. Some of these alliances consist of production sourcing agreements between fabless and foundry firms, whereas others cover the development and transfer of process technology among firms. These data unfortunately do not include alliances focused on collaborative product development between fabless semiconductor firms and systems firms. The alliance data also lack information on the revenues, investments, or assets associated with individual alliances, which means that we are unable to weight individual alliances by some measure of their economic importance. In spite of these problems, the ICE data have some advantages. They enable us to track the dissolution as well as the formation of alliances, and thus provide information on both the rate of new alliance formation and the “stock” of semiconductor industry alliances in existence during our sample period.

Figure 9 displays the number of newly formed and ongoing alliances in the semiconductor industry during the period 1990-1999. The number of alliances grew during the early 1990s, reached a peak during the middle of the decade, and has gradually declined since 1995 as the rate of alliance formation has decreased.



**FIGURE 9** Semiconductor industry alliances, 1990-1999. SOURCE: Integrated Circuit Engineering (ICE).

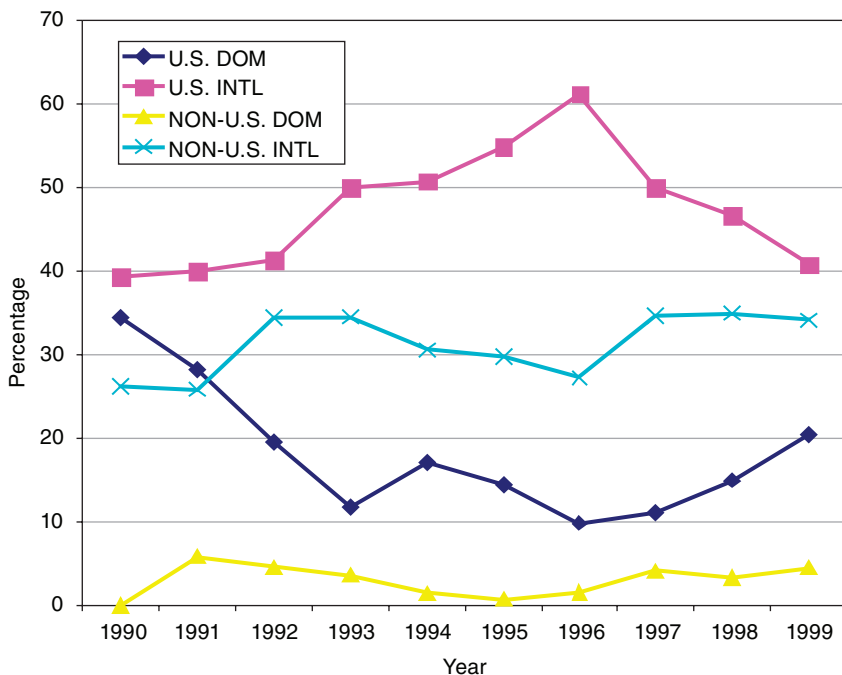


**FIGURE 10** Home region of semiconductor alliance participants, newly formed alliances, 1990-1999. SOURCE: Integrated Circuit Engineering (ICE).

The annual “stock” of alliances in operation averaged more than 400 during the period 1990-1999.

The regional composition of alliances also changed substantially during the 1990s. Figure 10 depicts trends in the regional composition of alliance partner firms for newly formed alliances during the period 1990-1999, based on partner-firm home countries. The share of North American firms in newly formed alliances decreased from roughly 70 percent in 1990 to slightly more than 50 percent in 1999, while the share of European and Southeast Asian firms increased.

Figure 11 disaggregates the stock of alliances in Figure 9 by the nationality of the firms participating in them. Domestic alliances are those in which all partner firms are headquartered in the same country, and international alliances are those for which at least one partner firm is headquartered in a different country. U.S. domestic alliances declined from roughly 35 percent of semiconductor industry alliances in 1990 to slightly more than 20 percent in 1999, although the 1999 share represented an increase from its low point of 10 percent in 1996. The share of alliances between U.S. and non-U.S. firms (“U.S. Intl”) within total industry alliances was essentially unchanged in 1999 from its 1990 level of 40 percent, although this share grew to more than 60 percent by 1996 before declin-



**FIGURE 11** Home region of semiconductor industry alliance participants, alliance “stock,” 1990-1999. SOURCE: Integrated Circuit Engineering (ICE).

ing. The share of non-U.S. domestic alliances also declined during the period 1990-1999, while non-U.S. international alliances increased from slightly more than 25 percent of total alliances in 1990 to roughly 35 percent by 1999.

Taken together, Figures 9, 10, and 11 suggest a slowdown in the rate of formation of alliances for R&D and technology development by all firms in the semiconductor industry during the 1990s, keeping in mind that we lack information on the size or economic significance of individual alliances. But the behavior of U.S. and non-U.S. semiconductor firms presents some contrasts that are not well understood. U.S. semiconductor firms experienced a period of significant growth during the early 1990s in their international alliance activities, followed by a decline in international alliance formation. These trends contrast with those for non-U.S. firms, which appear to have expanded their share of the shrinking number of newly formed international alliance activities throughout the 1990s. Non-U.S. firms also use alliances to team with firms from other nations or regions. If anything, globalization through alliances therefore appears to have been more persistent and intensive for non-U.S. semiconductor firms during the latter half of the 1990s.

Another analysis of alliance formation during the late 20th century by Hagedoorn (2002) used a different source of data but also concluded that the share of international undertakings declined from the 1980s through the 1990s. Moreover, Hagedoorn found that “information technology” R&D alliances (including semiconductors and a number of other industries) were less likely to involve cross-border relationships than was true of other sectors. The reasons for the apparent decline in the propensity of semiconductor firms to enter international R&D alliances, along with the (apparently) lower rate of formation of international R&D alliances by firms in semiconductors and related industries, remain unclear. Hagedoorn’s (2002) examination of R&D alliance data also does not shed light on the relative importance of participant firms from the United States and other industrial economies. Nonetheless, the results of the Hagedoorn analysis are broadly consistent with our findings, suggesting that this vehicle for globalization of innovation-related activities in the semiconductor industry declined somewhat in importance during the 1990s, especially for U.S. firms.

## Patenting

Patents, our final indicator of globalization in innovation, are an input to the innovation process rather than a direct measure of innovation. Nevertheless, these data, which are based on the semiconductor technology classification developed by the U.S. Patent and Trademark Office (USPTO), have several useful features, not least in making it possible to locate the site of the inventive activity that resulted in the patent. We are also able to weight our patent observations by various citation-based measures of the significance of individual patents, to control

somewhat for the skewed distribution of patents by economic or technological importance.<sup>4</sup>

The semiconductor industry is a high-technology sector for which patents for many years were viewed as unimportant, reflecting the fact that (among other things) much of the most important innovative activity related to process innovation was protected through secrecy or inimitability, and cross-licensing of patents was widespread. As Hall and Ziedonis (2001) point out, however, patenting by both IDMs and fabless semiconductor firms grew rapidly during the 1980s, following changes in U.S. patent policy and some large financial awards in patent-infringement cases. We therefore believe that the period covered by our patent analysis is one during which semiconductor firms patented extensively, and patents therefore should serve as a reasonable proxy for inventive activity.

Our empirical analysis utilizes patents assigned to 217 U.S. and non-U.S. semiconductor firms during the period 1991-2003 (based on year of application). This dataset includes almost 114,000 patents from more than 80 patent classes, as identified by the USPTO's Office of Technology Assessment and Forecast and Hall and Ziedonis. (The Appendix in this chapter lists the patent classes included in our dataset.) We also collected data on citations to these patents in subsequently issued patents in all patent classes.

We use information on the location of the inventors listed on each patent as an indicator of the site of the inventive activity that produced the patent. Based on a comparison of the reported site of the invention with the headquarters location for each company in our dataset, each patent is assigned to one of the following mutually exclusive categories.

- **Domestic Patents:** patents whose inventors are all located in the home country of the controlling company;
- **Foreign Patents:** patents whose inventors are all located in countries other than the home country of the controlling company; and
- **International Collaboration Patents:** patents that have at least one inventor located in the home country and at least one inventor located in another country.<sup>5</sup>

We corrected patent data for self-citations (excluding citations to other patents filed by the assignee), and created forward citation windows of 2, 3, and 4

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<sup>4</sup>Patent citation data were collected with the help of the Metrics Group Division of UTEK-EKMS, an IP strategy company based in Boston.

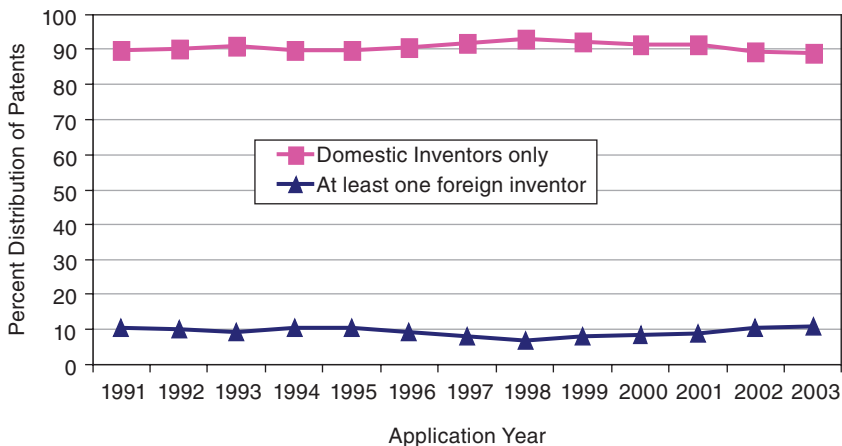
<sup>5</sup>Bergek and Bruzelius (2005) argue that the "inventor location" data often yield misleading information, because of firm-specific differences in the attribution of patents to inventors or inventor mobility between the time of application and the time of issue of the patent. It is plausible that such "noise" may affect inferences from cross-sectional analyses of patent data. We use the "inventor location" information for longitudinal analysis, however, and there is little reason to believe that the problems identified by Bergek and Bruzelius have become significantly more severe during the time period of this analysis.

years after publication for each patent, yielding a total of 402,865 forward citations that omit self-citations. In our citation analysis that follows, we use a 3-year “window” for patent citations (i.e., we limit the count of citations to those in the first 3 years after the year of issue of the relevant patent).

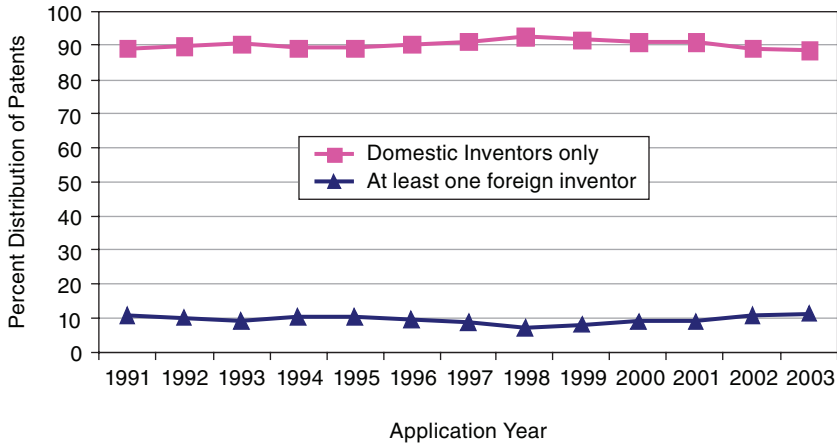
Any comparisons of patents issued to U.S. and non-U.S. firms must be interpreted carefully. For most non-U.S. firms, the higher costs of seeking a patent in the United States in addition to a home-country patent mean that U.S. patent protection will be obtained for only the more valuable patents in these firms’ portfolios. A simple comparison of U.S. patents assigned to U.S. firms with those assigned to non-U.S. firms thus may yield misleading results because of the different underlying “quality” of the two patent groups.

Accordingly, our comparisons of U.S. patents assigned to U.S. and non-U.S. firms use only U.S.-assigned patents with “equivalents” in either the Japanese Patent Office (JPO) or the European Patent Office (EPO). In other words, our discussion of U.S. and non-U.S. semiconductor firms’ patenting that follows (but only that discussion) includes only the semiconductor patents assigned to U.S. firms for which a patent on the same or a very similar invention also has been issued in one of these other major markets. We used the Delphion international patent database to identify U.S.-assigned patents for which an equivalent patent has been issued by either the JPO or the EPO.

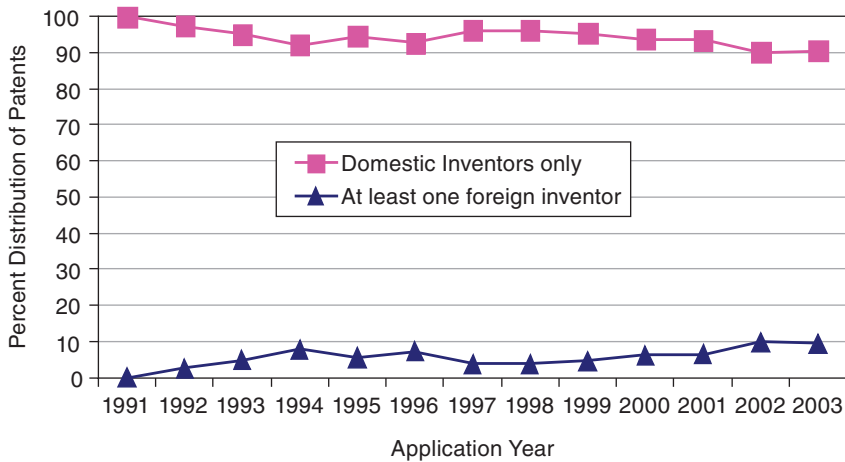
Figure 12 depicts trends during the period 1991-2003 in the share of all semiconductor patents assigned to U.S. firms that were created by domestic inventors (either an individual located in the United States or an “all-domestic” inventor team) and the share of semiconductor patents assigned to U.S. firms that involved



**FIGURE 12** Domestic and offshore U.S.-assigned semiconductor patents, 1991-2003  
SOURCE: Thomson Delphion Consulting.



**FIGURE 13** Domestic and offshore U.S.-assigned semiconductor patents, IDM and systems firms, 1991-2003. SOURCE: Thomson Delphion Consulting.



**FIGURE 14** Domestic and offshore U.S.-assigned semiconductor patents, fabless firms, 1991-2003. SOURCE: Thomson Delphion Consulting.

at least one offshore inventor (combining foreign and international collaborative patents). The absence of any strong trend during the decade in this measure of offshore inventive activity is striking—the domestic share remains stable at roughly 90 percent throughout the period. A similar lack of growth in offshore inventive activity also is apparent in Figure 13, which shows the same “site of invention” trends for the IDM and systems firms in our sample. Although the number of patents for fabless firms in our sample is considerably smaller, Figure 14 reveals

**TABLE 3** Firm HQ and Location of Inventive Activity, U.S. Patents

		One Inventor Located in								
1994-2003		USA	Europe	Japan	Taiwan	Korea	Israel	Canada	Singapore	Others
Firm HQ in	USA	86.5%	6.5%	3.8%	0.2%	0.2%	0.9%	0.4%	0.3%	0.7%
	Europe	28.4%	60.0%	1.5%	7.1%	1.3%	0.2%	0.3%	0.5%	0.4%
	Japan	4.2%	0.7%	94.8%	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%
	Taiwan	7.6%	0.1%	1.0%	90.7%	0.1%	0.0%	0.0%	0.1%	0.5%
	Korea	2.5%	0.1%	0.5%	0.0%	96.1%	0.0%	0.1%	0.1%	0.8%
	Israel	5.3%	0.0%	0.0%	0.0%	0.0%	91.6%	3.1%	0.0%	0.0%
	Canada	13.3%	19.1%	1.2%	0.0%	0.0%	0.0%	66.5%	0.0%	0.0%
	Singapore	18.5%	1.0%	0.0%	0.0%	0.0%	0.0%	0.0%	80.4%	0.3%
			One Inventor Located in							
1996-1999		USA	Europe	Japan	Taiwan	Korea	Israel	Canada	Singapore	Others
Firm HQ in	USA	86.9%	6.4%	4.1%	0.1%	0.2%	0.7%	0.4%	0.4%	0.5%
	Europe	30.6%	57.2%	1.4%	9.1%	0.6%	0.3%	0.2%	0.3%	0.3%
	Japan	4.2%	0.7%	94.8%	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%
	Taiwan	9.2%	0.1%	1.5%	88.7%	0.0%	0.0%	0.0%	0.0%	0.4%
	Korea	2.4%	0.0%	0.5%	0.0%	96.1%	0.0%	0.0%	0.0%	0.9%
	Israel	6.7%	0.0%	0.0%	0.0%	0.0%	88.9%	4.4%	0.0%	0.0%
	Canada	13.1%	20.4%	1.5%	0.0%	0.0%	0.0%	65.0%	0.0%	0.0%
	Singapore	25.0%	0.8%	0.0%	0.0%	0.0%	0.0%	0.0%	73.9%	0.8%
			One Inventor Located in							
2000-2003		USA	Europe	Japan	Taiwan	Korea	Israel	Canada	Singapore	Others
Firm HQ in	USA	85.1%	8.1%	3.8%	0.2%	0.2%	0.3%	0.3%	0.2%	0.9%
	Europe	23.8%	62.6%	2.0%	6.4%	2.7%	0.2%	0.5%	0.7%	0.7%
	Japan	4.0%	0.8%	95.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%
	Taiwan	5.7%	0.1%	0.5%	92.8%	0.2%	0.0%	0.0%	0.2%	0.3%
	Korea	8.7%	0.0%	0.0%	0.0%	82.6%	0.0%	0.0%	4.3%	4.3%
	Israel	3.8%	0.0%	0.0%	0.0%	0.0%	94.9%	1.3%	0.0%	0.0%
	Canada	16.0%	15.4%	0.6%	0.0%	0.0%	0.0%	67.9%	0.0%	0.0%
	Singapore	14.2%	1.4%	0.0%	0.0%	0.0%	0.0%	0.0%	84.5%	0.0%

SOURCE: Thomson Delphion Consulting.

a modest shift toward greater offshore inventive activity among fabless firms.<sup>6</sup> Even for this group of firms, however, patenting remains dominated by home-country inventive activity.

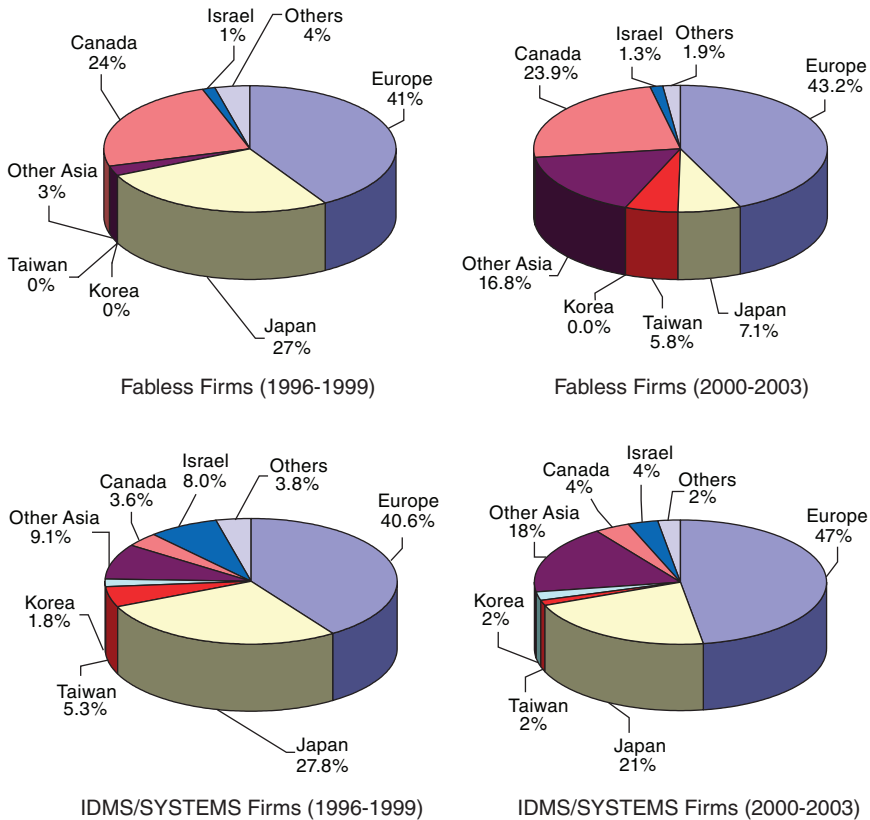
Table 3 includes patents assigned to U.S. (for which an international “equiva-

<sup>6</sup>We also analyzed the share of forward citations accounted for by the “home-invented” and “offshore participant” subsamples in our patent database. Interestingly, citations are proportionate to the patent shares (i.e., there is no evidence that home-invented patents are cited much more intensively than those for which offshore inventors are involved).

lent” patent, as defined earlier, was found) and non-U.S. firms, disaggregating the data by home country of patent assignee and site of inventive activity for 1994-2003, and further splitting the data into 1996-1999 and 2000-2003 subperiods. Japanese firms’ inventive activity is dominated by home-country inventors to a greater extent than is true of either U.S. or European semiconductor firms for the 1994-2003 period. Japanese inventors are listed on almost 95 percent of Japanese firms’ U.S. patents, whereas U.S. inventors are listed on almost 87 percent of U.S. patents and European inventors appear on 60 percent of European firms’ U.S. patents. Looking at the off-diagonal portions of Table 3, European inventors account for almost twice as large a share of U.S. semiconductor firms’ patents as Japanese inventors. U.S. inventors appear on nearly 30 percent of European firms’ U.S. patents, and Japanese inventors on less than 2 percent. A comparison of the two subperiods does not reveal significant differences, although there is some indication that the “homeboundness” of the inventive activities of European, Japanese, and Taiwanese semiconductor firms is increasing slightly. For all but Canadian semiconductor firms, the single most important offshore site for inventive activity is the United States, which on the basis of this evidence remains the dominant site for the offshore inventive activities of most non-U.S. semiconductor firms. For U.S. semiconductor firms, the leading offshore site for inventive activity in both the 1996-1999 and the 2000-2003 subperiods is Europe, followed closely by Japan.

Figure 15 depicts the leading locations of offshore inventors in the semiconductor patents assigned to U.S. firms for the 1996-1999 and 2000-2003 subperiods. The figure highlights considerable change in these locations over time and differences in the location of offshore inventive activity between fabless and other firms in the U.S. semiconductor industry. Canadian inventors play a more prominent role in the offshore patenting of U.S. fabless firms than is true of IDM and systems firms, accounting for less than 4 percent of the offshore inventive activity of IDMs and system firms versus more than 20 percent for fabless firms, in both periods. The Japanese share of U.S. fabless firms’ offshore patenting also declines between the two subperiods, perhaps reflecting the growth in systems design in non-Japanese Asia (notably Taiwan, South Korea, and Singapore). European inventors are of comparable importance for both U.S. IDMs and U.S. fabless firms in both time periods. A comparison of the two subperiods for both groups of firms also highlights the shift in the importance of non-Japanese Asian inventors. The share of “other Asia” inventors (particularly Singapore) for fabless firms increases more than sixfold (albeit from a very modest initial level), and the “other Asia” share for IDMs and systems firms nearly doubles.

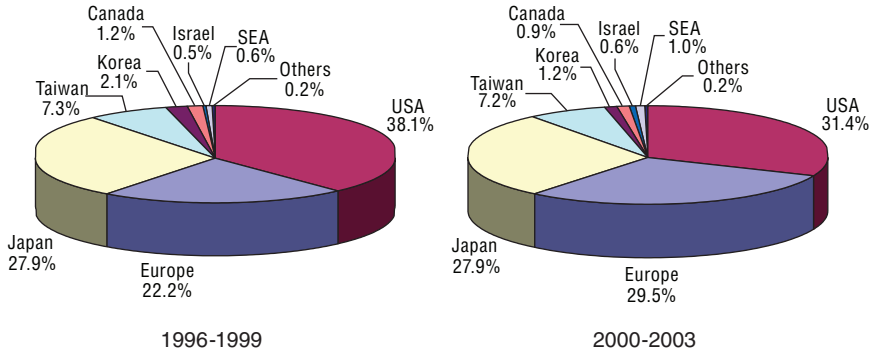
Figures 16 and 17 compare the invention locations for U.S. semiconductor patents assigned to U.S. and non-U.S. firms, using only the U.S.-assigned patents for which an international “equivalent” patent exists. The data in the figures are based on a random sample of 5,000 patents from the semiconductor patent portfolios of Asian, European, and U.S. firms. The random-sampling procedure, which



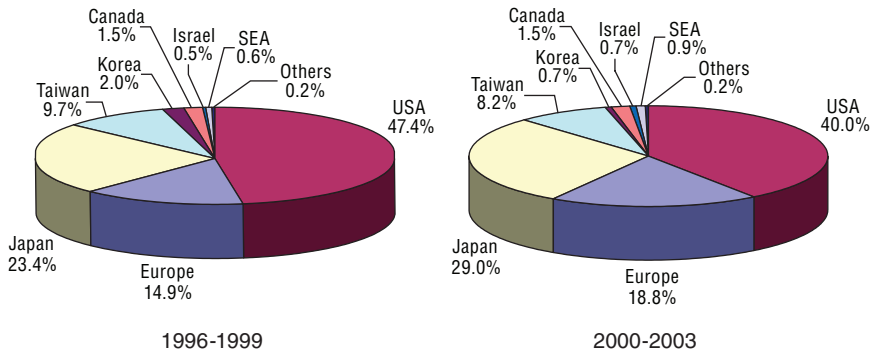
**FIGURE 15** Offshore invention sites, U.S.-assigned semiconductor patents, 1996-2003  
 SOURCE: Thomson Delphion Consulting.

is stratified by year and patent class within our overall semiconductor-patent “family,” was adopted to provide a patent sample that was not affected by the different propensities of U.S., Asian, and European firms to obtain foreign as well as domestic patents. Figure 16 displays data on the reported site of inventions for the 1996-1999 and 2000-2003 subperiods, and Figure 17 displays data on the shares of citations within the first 3 years after issue for these patents. Although the United States is the largest single site of inventive activity resulting in patents throughout the 1996-2003 period, its dominance declines modestly between the 1996-1999 and 2000-2003 subperiods. The share of patents attributable to Japanese or Taiwanese sites is essentially unchanged throughout the 1993-2003 period, whereas the European share of inventive activity increases between the 1996-1999 and 2000-2003 subperiods.

Comparing the shares of patents with the shares of citations in Figure 17



**FIGURE 16** Distribution of invention sites, all USPTO semiconductor patents, 1996-1999.



**FIGURE 17** Distribution of citations by invention site, all USPTO semiconductor patents, 1991-2003. SOURCE: Thomson Delphion Consulting and UTEK-EKMS.

reveals that patents from Japanese and European invention sites tend to be “underrated” (their share of citations is smaller than their share of overall patents), whereas U.S. patents are “overcited” relative to their share of overall patenting. Patents with Taiwanese invention sites are cited slightly more intensively relative to their share during the 2000-2003 subperiod.

Overall, the results of our analysis of the site of inventive activity resulting in U.S. patents support the original findings of the analysis of patenting by firms from a broader sample of industries by Patel and Pavitt (1991), who found that large multinational firms’ patenting was dominated by home-based inventive activity. The evidence on post-issue citations suggests that the most “important” semiconductor patents are slightly more likely to result from domestic inventive activity, but this conclusion should be qualified by a recognition of the small size

of the sample on which it is based. The trends in patenting for fabless firms suggest that the demanding requirements for close collaboration between semiconductor component designers and systems firms may be causing some shift within this segment of the semiconductor industry toward greater reliance on foreign inventive activity in patenting; but any such trend is very modest. Although additional analysis is required, this finding concerning fabless firms' offshore patenting is consistent with the "market demand-exploitation" motive for locating R&D offshore discussed by Gerybadze and Reger (1999)—an important factor in the location of firms' R&D is their need to be near their innovative customers.

### IMPLICATIONS FOR ENGINEERING EMPLOYMENT

The evidence presented in this chapter suggests that globalization and structural change in the semiconductor industry have resulted in significant growth in offshore manufacturing capacity, much of which remains owned by U.S. producers. But this growth in offshore production capacity has had far less significant effects on the location of innovation-related activities within the semiconductor industry, including the innovation-related activities of U.S. semiconductor firms. Indeed, the growth of offshore foundry production capacity in Southeast Asia has helped sustain the growth of employment of engineers and designers in U.S.-based fabless semiconductor firms.

Innovation-related activities in this industry include a number of different activities, such as semiconductor chip design, process-technology development, and product-technology development. The limited evidence on these three activities discussed earlier in this chapter suggests that semiconductor chip design is the least "homebound" of the three. Process-technology development, as measured by the siting of development fabs, does not appear to have moved offshore to any extent, while patenting (which includes product- and process-technology development) also displays little evidence of significant offshore relocation.

A recent analysis of engineering-employment trends in the U.S. semiconductor industry (Brown and Linden, 2006b) suggests that the employment effects of shifts in the location of chip design for U.S. engineers have been modest thus far. Brown and Linden (2006b) found that employment and earnings growth were higher during the 2000-2005 period for engineers employed in the U.S. semiconductor industry than in other U.S. industries. Employment growth during this period was strongest for electrical, computer hardware, and electronic engineers, but was negative for industrial engineers within the semiconductor industry. Brown and Linden (2006b) report some evidence that median earnings for "mature" engineers (50 years and older) employed in the semiconductor industry are lower than for younger engineers, but this tendency appears throughout the time period (2000-2004) that they analyze, rather than becoming more pronounced in the most recent year. Moreover, interpreting these trends is difficult, since they reflect some tendency for engineers to move into management positions as they

mature. The individuals classified as “engineers” among this older cohort thus have remained out of management, which may affect their reported earnings.

Similarly to many other dimensions of globalization of innovation-related activities in the semiconductor industry, the available data are not well suited to analysis of the employment effects of any movement of different categories of innovation-related activities to non-U.S. locations. The most detailed analysis of employment trends in the U.S. semiconductor industry during the 2000-2005 period does not reveal significant erosion in engineering employment or earnings during the period (Brown and Linden, 2006b). The available evidence, imperfect as it is, thus does not support grave concern about the employment consequences of recent shifts in the location of innovation-related activities in the semiconductor industry.

The U.S. employment data are largely “backward-looking” indicators of the employment consequences of globalization of innovation-related activities in the semiconductor industry. The implications for future engineering employment trends in the U.S. semiconductor industry associated with the growing numbers of design engineers in China, India, and Taiwan are unclear (Brown and Linden, 2006b). Despite government sponsorship and local access to systems firms, China’s chip design capabilities do not yet represent a viable product design outsourcing alternative. India offers certain product design advantages given the predominant use of the English language and its thriving software sector, but zero government involvement, limited manufacturing capacity, and no major fabless firm presence have hampered success. Taiwan appears best poised to become a viable offshoring and outsourcing alternative, as well as a significant competitive threat, to U.S. semiconductor firms in the near term, given its focused government programs, locally owned fabless design segment, and close proximity to systems houses and foundries. These factors suggest that U.S. semiconductor firms’ dominance in product design could be challenged in the future, potentially reducing U.S. employment in this innovation-related activity. But here too, even a partial “hollowing out” of the U.S. product design segment seems unlikely.

### **IMPLICATIONS FOR FIRM STRATEGY AND PUBLIC POLICY**

An earlier study of the U.S. semiconductor industry’s innovative and competitive performance (Macher et al., 1999) noted that U.S. firms’ development of new products (including microprocessors and digital-signal processing chips) and new business models (notably the growth of fabless firms) had enabled them to overcome a significant competitiveness crisis during the late 1980s and early 1990s. U.S. semiconductor firms remain globally competitive in the face of rapid innovation by non-U.S. semiconductor firms, but structural change in the global semiconductor industry has resulted in considerable change in the structure of the innovation process.

Fabless firms in particular seek to develop closer collaborative relationships

with major systems firms based outside of the United States. Shorter product life cycles and the increased variety of individually smaller applications that utilize semiconductor components mean that the IDMs face greater risks from swings in demand as the costs of their production facilities continue to rise. The design and (especially) the manufacturing capabilities of foreign regions also have improved significantly since the 1980s, creating new opportunities for U.S. firms to exploit a global division of labor in semiconductor design and manufacturing. Among other things, this emergent division of labor has supported the rapid growth of fabless semiconductor firms in the United States.

In contrast to the industry challenges of the 1980s that threatened the viability and very survival of the U.S. semiconductor industry, the challenges of the early 21st century stem from the need to manage this global division of labor effectively and strategically while maintaining leadership in innovation. These challenges are hardly new, as lower-productivity, labor-cost-sensitive functions in many U.S. manufacturing industries (and a growing array of U.S. nonmanufacturing industries, such as software and financial services—see Chapters 2 and 10, respectively) have moved to lower-cost areas of the global economy. Many of these regions have developed strong educational and economic infrastructures that can support the creation of productive labor forces and contribute to such innovation-related activities as product design and process engineering.

The offshoring and outsourcing of various activities by U.S. firms has a long history, but so too do the innovative responses of successful U.S. firms. Even as the more cost-sensitive, lower-value-added activities have been shifted to offshore locations, U.S. firms have maintained their global competitiveness by developing and introducing innovative new products (e.g., PCs and communications) and business models (e.g., fabless semiconductor firms). In the semiconductor industry, product innovation will remain central, and manufacturing-process innovation is likely to focus on a narrower range of products in which U.S. IDMs remain dominant. In other words, the strategic management of innovation becomes even more important for the competitive performance of semiconductor firms that seek to exploit the emerging global division of labor in product design and manufacturing while maintaining strength in product and process innovation.

It seems likely, for example, that the remaining U.S. IDMs will continue to exploit offshore sites for manufacturing while relying on foundries to serve a larger portion of their production requirements for products that are slightly behind the “bleeding edge” of technology—the “fab-lite” model of production. The continuing growth of semiconductor foundries will provide further opportunities for expansion by U.S. fabless firms, although these firms also are likely to shift at least some of their design-related activities to offshore locations because of the presence of major customers in these areas.

In spite of the powerful forces that are shifting some design, manufacturing, and other functions to offshore locations, the bulk of U.S. semiconductor firms’ “inventive activity” did not shift during the 1990s. As measured imperfectly

by the reported residence of inventors listed on U.S. patents, the inventive activities of U.S. semiconductor firms remain concentrated in the United States. Moreover, the inventive activities of non-U.S. semiconductor firms, as measured by similar information for their U.S. patents, also appear to be concentrated in their home countries. This tendency for inventive activity to remain homebound was first pointed out in an analysis by Patel and Pavitt (1991) of patenting by multinational firms. The “nonglobalization” of patenting activity seems to reflect the strong dependence of inventive activity on domestic sources of fundamental research and skilled researchers. Despite remarkable advances in the codification and global transmission of scientific research, access to such research results for purposes of inventive activity remains surprisingly national in scope. And the apparent importance of the national science and engineering base for domestic inventive activity reinforces the importance of another key governmental function—funding the scientific and engineering research and education that support this domestic knowledge pool.

The most important implications of this study for U.S. public policy thus relate to (1) the importance of continued (and arguably renewed) federal funding for R&D in the engineering and physical sciences in industry and universities and (2) the importance of public support (which may be financial or regulatory) for more rapid development of the “information infrastructure” (e.g., broadband communications) that can support the growth of a large domestic market of demanding and sophisticated consumers that will in turn spawn innovations in information and electronics technologies.

Much of the remarkable record of innovation in the U.S. semiconductor and related IT industries that spans the 1945-2006 period rested on substantial investments of public funds in R&D that supported industrial research and innovation, as well as the training of generations of engineers and scientists. Much of this federal R&D investment was linked to national-security goals, and the end of the Cold War and associated defense “build-down” led to significant reductions in growth and in some cases the level of federal funding for R&D in the physical and engineering sciences, especially in academic institutions. Growth in federal R&D investment since the late 1980s has been dominated by growth in biomedical R&D funding. Although a portion of this biomedical R&D investment has supported education and training in the physical sciences and engineering, the imbalance in investment trends, if not reversed, could have detrimental consequences for the continued innovative vitality of the U.S. semiconductor industry and related industries.

The importance of market demand in the locational structure of innovation in the semiconductor industry and other high-technology industries (see Chapters 8, 9, and 10, which illustrate the importance of local demand in service industries as well) is difficult to overstate. We have noted that the declining share of semiconductor consumption accounted for by the PC has been associated with the growth of new markets for semiconductor components (e.g., wireless com-

munications devices) that involve major non-U.S. systems firms. Moreover, many of the most innovative, demanding, and sophisticated users of such devices now are located in non-U.S. markets (e.g., South Korea for wireless devices, or Finland for broadband-based applications). Historically, U.S. semiconductor firms have derived enormous competitive advantages from their ability to serve (and learn from) a large domestic market populated by sophisticated and demanding users—in some cases, these demanding users were major institutions, such as the military.

One important reason for the rapid development of browser-based applications and new business models in the early days of the World Wide Web, which relied on innovations developed in Europe, was the broad diffusion and low cost of PCs within the United States, as well as the low costs of accessing computer networks (Mowery and Simcoe, 2002). Government policy can play a significant role in the creation or support of markets for advanced technologies (recall that the Internet was aided by substantial federal as well as private funding) by supporting investment in the infrastructure that proved so fruitful in the early days of computer networking and developing regulatory policies that create incentives for the large private investments in the communications infrastructures needed for the emergence of new applications, products, and services. R&D and related investments from around the globe are likely to flow to markets in which users demand the most advanced technologies and where these users have access to an array of options for developing new applications of these technologies. Such markets are likely to rely in part on a sophisticated wireless and high-speed broadband communications infrastructure.

## CONCLUSION

The U.S. and global semiconductor industries have experienced significant structural change since 1980 with the growth of specialized design and manufacturing firms. The growth of new products that use semiconductor components and the entry of firms from Southeast Asia also have contributed to growth in offshore manufacturing capacity within the industry, much of which remains under the control of U.S. semiconductor firms. Nevertheless, there is surprisingly little evidence that the innovation-related activities of U.S. semiconductor firms have moved offshore to a comparable extent. Overall, the results of this descriptive examination of an array of measures of the “globalization” of innovation-related activities in the semiconductor industry support the findings of Patel and Pavitt (1991) from more than a decade ago. The innovation-related activities of otherwise global firms in this industry remain remarkably nonglobalized, even in the face of expanded international flows of capital and technology, far-reaching change in the structure of semiconductor manufacturing, and significant shifts in the structure of demand.

How can one explain these findings? The homebound nature of process inno-

vation investments is perhaps the least surprising, given the complexity of process technology within the semiconductor industry and the demanding requirements for coordination between product and process innovation. Moreover, the emergence of vertically specialized foundries that do not rely on development facilities to the same extent as IDMs means that our data on the location of development fabs exclude process innovation in a segment of semiconductor manufacturing that has grown considerably and gives every indication of continued growth. It is also important to highlight the retrospective nature of these indicators, which (especially in the case of patents) reflect R&D and related investments made years before their effects appear in these data. Trends in patenting in the late 1990s thus reflect actions or strategies that were put in place in the early 1990s and, like most other scholars, we have almost no forward-looking indicators.

Some of our other indicators, such as the NSF R&D investment data, exclude non-U.S. firms, and the data themselves may well omit significant innovation-related activities. It is plausible, for example, that much of the design work of U.S.-based fabless firms is not captured by the NSF R&D surveys. U.S.-based semiconductor firms also benefit from the strength of their home-based innovation system, especially in the product design area. "Home-base augmentation" (Kuemmerle, 1999) thus may be a relatively minor factor for U.S. firms' R&D investment strategies and a significant motive for non-U.S. firms' R&D investments in the United States and elsewhere. Moreover, the exploitation by U.S. semiconductor firms of these "home-base" advantages may not require significant offshore R&D investment to complement offshore production investment. Indeed, one hypothesized motivation for offshore R&D that receives the most support from our analysis is the "market-demand exploitation" hypothesis of Gerybadze and Reger (1999), which may be particularly relevant to the patenting activities of U.S.-based fabless firms.

The trends highlighted in our discussion of technology-development and R&D alliances in this industry also raise interesting questions. The declining rate of formation of domestic and international alliances by semiconductor firms throughout the industry is surprising but may reflect some exhaustion of the pool of potential alliance partners or projects. Nontariff barriers to U.S. firms' access to foreign markets resulting from government procurement restrictions or other policies have been reduced during the past decade in several industries (OECD, 2005), and it is possible that these reductions in market-access barriers have reduced U.S. firms' incentives to pursue collaborative ventures with non-U.S. firms. Our alliance data also do not fully capture the types of alliances that are important to the fabless firm segment of the U.S. semiconductor industry, and thereby understate the significance of international alliances within the overall industry. These data nevertheless suggest some growth in the participation by non-U.S. firms in domestic and foreign alliances, especially among non-Japanese Asian firms. Some portion of this alliance activity may be motivated by access to the Chinese mainland market, where nontariff barriers remain significant.

The results of our analysis of patents provide the strongest support for the original findings of Patel and Pavitt (1991), but these results also must be treated with caution. As we pointed out earlier, patents omit many of the innovation-related activities that are most important to the creation or maintenance of competitive advantage for IDMs and fabless firms alike, and our findings for these indicators accordingly must be qualified.

Does the nonglobalized character of U.S. semiconductor firms' innovation-related activities differ significantly from that of semiconductor firms based in other nations? The data presented in Table 3 indicate that the homebound character of U.S. semiconductor firms' patenting is similar to that of semiconductor firms headquartered in other nations, as is the homebound character of the process-technology development facilities that U.S. and non-U.S. IDMs and systems firms operate.

Are the trends discussed in this paper for the semiconductor industry representative of other high-technology industries, or is this industry unique? Comparing the extent of "nonglobalization" in the semiconductor industry with that of other knowledge-intensive industries is difficult, since few detailed studies of these trends have been undertaken for other industries. Offshore R&D investment by U.S. firms in electronic components accounted for a smaller share of industry-funded R&D during the 1990s than is true of U.S. firms in pharmaceuticals, where more than 14 percent of industry-funded R&D was performed offshore in 2001 (National Science Board, 2006). Like semiconductors, the pharmaceuticals industry underwent considerable structural change and vertical specialization during the 1990s (see Chapter 6), particularly through the entry of biotechnology firms that often specialize in drug discovery and contract research organizations that specialize in drug development (i.e., clinical trials). Unlike semiconductors, however, the structure of market demand in pharmaceuticals has undergone little significant change—the U.S. remains the most profitable single national market, thanks to the peculiar structure of its health care delivery system.

Why do we observe such contrasts between these two industries in the (apparent) share of offshore sites in innovation-related activities? One hypothesis appeals to the more diverse structure of products in the pharmaceuticals industry, combined with substantial scientific research capabilities (in many cases, based on public funding) in many non-U.S. industrial economies. The science underlying product innovation in various therapeutic classes, to say nothing of the growing variety of delivery mechanisms (topical, inhaled, subdermal, as well as oral), arguably spans a wider variety of fields and has become much more diverse during the past 20 years than is true of product innovation in semiconductors. These factors have supported the growth of significant clusters of scientific expertise in specific therapies or diseases that attract the R&D investments of U.S. pharmaceuticals firms. A large part of the "D" in pharmaceutical R&D also represents costs associated with conducting and administering clinical trials to diverse patient populations. The situation in semiconductors arguably is

quite different—the structure of products and markets remain less complex, and government R&D programs have not created comparably accessible clusters of scientific and technological expertise.

As this speculative discussion suggests, the dynamics of globalization and nonglobalization in innovation are complex and reflect contrasting paths of evolution (at the industry level) within different national innovation systems, as well as the interplay among these national innovation systems, trade policy, and other influences. Still another important influence on the globalization of at least some types of pharmaceuticals R&D is regulatory policy in the offshore as well as domestic markets in which all global pharmaceuticals firms operate. Maintaining a significant R&D presence in their offshore markets may facilitate the management of clinical trials for new products that U.S. firms seek to introduce into these markets.

Even in the pharmaceuticals industry, however, Narin et al. (1997) have pointed out that the patents filed in the United States by non-U.S. (as well as U.S.) inventors tend to rely disproportionately on “home-country” science, as measured by the citations to scientific publications in their patent applications. The links between science and technology that contribute to much of the inventive activity that is embodied in patenting retain a considerable homebound element, rather than operating seamlessly and frictionlessly across national boundaries.

Overall, this discussion of the globalization of innovation-related activities in the U.S. semiconductor industry does not indicate an imminent policy-related “crisis” in the innovative capabilities of U.S. firms. The implications of our discussion for the employment of engineers in innovation-related activities in the U.S. semiconductor industry also are reasonably positive. As we have noted repeatedly, U.S. firms have reacted to the growth of offshore innovative and productive capabilities by developing novel business models that have enabled them to compete successfully in an array of new markets. The success of these innovative strategies has sustained innovation and employment in the U.S. semiconductor industry. Nonetheless, it seems clear that much of the innovative performance of U.S. semiconductor firms relies on the health of a complex domestic R&D infrastructure that has benefited from large investments of public funds during the past six decades. A second important historical contributor to the innovative performance of U.S. firms is the large domestic market of innovative users that these firms face. Sustaining both of these factors that have contributed to the innovative performance of U.S. semiconductors in an intensely competitive global industry will require innovations in policy by both government and industry for decades to come.

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