The "Non-Globalization" of Innovation in the Semiconductor Industry

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The determinants, patterns, and consequences of globalization of the innovative activities of high-technology firms have been extensively studied.[1] Among the central questions this research addresses is the extent to which international flows of R&D investment and the offshore movement of other forms of innovative activity are linked with firms' foreign investments in manufacturing and related activities. A second important issue concerns measurement—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 article addresses these challenges by examining 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.[2] The results of our analyses highlight several distinctive trends in the globalization of innovation-related activities in this industry:

- There is little growth in the international share of R&D investment by U.S. firms in "electronics components" manufacturing (an industry category that includes semiconductors, along with several other electronics product segments) during 1985-2001.

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- 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.
- The patenting activity of large U.S. integrated semiconductor firms (those that both design and manufacture their products) remains predominantly "homebound," with little upward trend in offshore inventive activity in their patents during 1991-2003.
- Patenting by European, Japanese, and Taiwanese semiconductor firms is similarly dominated by domestic inventive activity and, if anything, this "home country" inventive activity bias has increased slightly during the 1996-2003 period.
- The patenting activity of U.S. "fabless" semiconductor firms, which design and market but do not manufacture their products, displays slight growth in offshore inventive activity during 1991-2003.
- 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.

Taken as a whole, our findings underscore the importance of a broad view of the diverse 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) is the emergence of new segments of market demand that are concentrated in Southeast Asia. However, 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 to a more diverse array of heterogeneous niches associated with the Internet and wireless communications applications. The share of industry production from "integrated device manufacturers" (IDMs) that both design and manufacture semiconductor components has declined; instead, a vertically integrated industry segment coexists with a vertically specialized segment. IDMs compete and often collaborate with firms that specialize in design and marketing ("fabless" firms) or manufacturing ("foundries"). Along with many other high-technology industries, market demand and technical expertise are growing in geographic regions (e.g., Malaysia, Taiwan, Singapore, and China) that formerly accounted for smaller shares of global demand for semiconductor components.

The Decline of the PC and Emergence of New Component Markets

The market for semiconductor components shifted during the 1990s from one dominated by computer applications (especially PCs) to a more fragmented market in which wireless communications and other non-PC consumer products occupy a more important role.[3] Most industry observers agree that non-PC markets for semiconductor components will continue to grow more rapidly than PC markets for the next decade.

Significant differences between PC and non-PC markets for semiconductor components suggest that this shift in consumption patterns will have important implications for the organization of the innovation process in the semiconductor industry. The PC market is characterized by an entrenched architectural standard (the so-called "Wintel" standard), which means that interfaces among semiconductor components and PC components have been relatively well defined and stable. This stable architectural standard does not apply to non-PC markets. 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 production capacity—the costs of which continue to rise—must become more flexible and capable of producing a wider variety of component designs without completely new equipment or production facilities.

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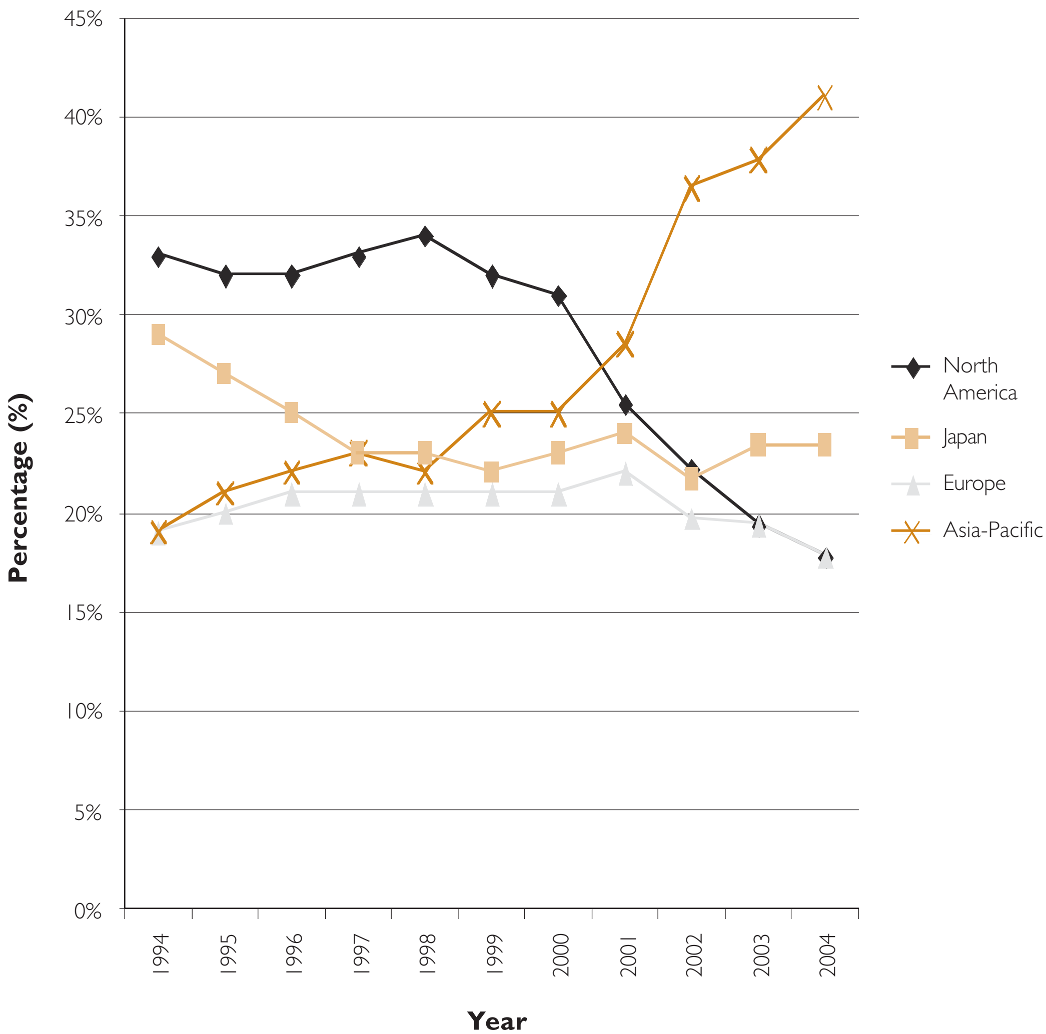
The relative decline of the PC market for semiconductors also has important implications for the geographic location of demand and design activity for semiconductor components. The PC market has been dominated by designs developed in the United States and by an architecture that remains largely under the control of U.S. firms. However, designers and producers of the systems for which markets are growing more rapidly (e.g., wireless communications) are more heavily concentrated in Southeast Asia, especially Taiwan, Japan, and Singapore. Figure 1 illustrates the shifting geographic structure of demand during 1994-2004, highlighting declines in the share of global chip consumption share accounted for by Japan and the United States and a corresponding rise in Southeast Asia's share.

FIGURE 1. Semiconductor End-Use Markets by Geographic Region, 1994-2004



Producers of these new consumer-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.[4] Moreover, the number of new applications using 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 no longer valid. As a result, close interaction between designers of components and designers (as well as producers) of these more heterogeneous 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

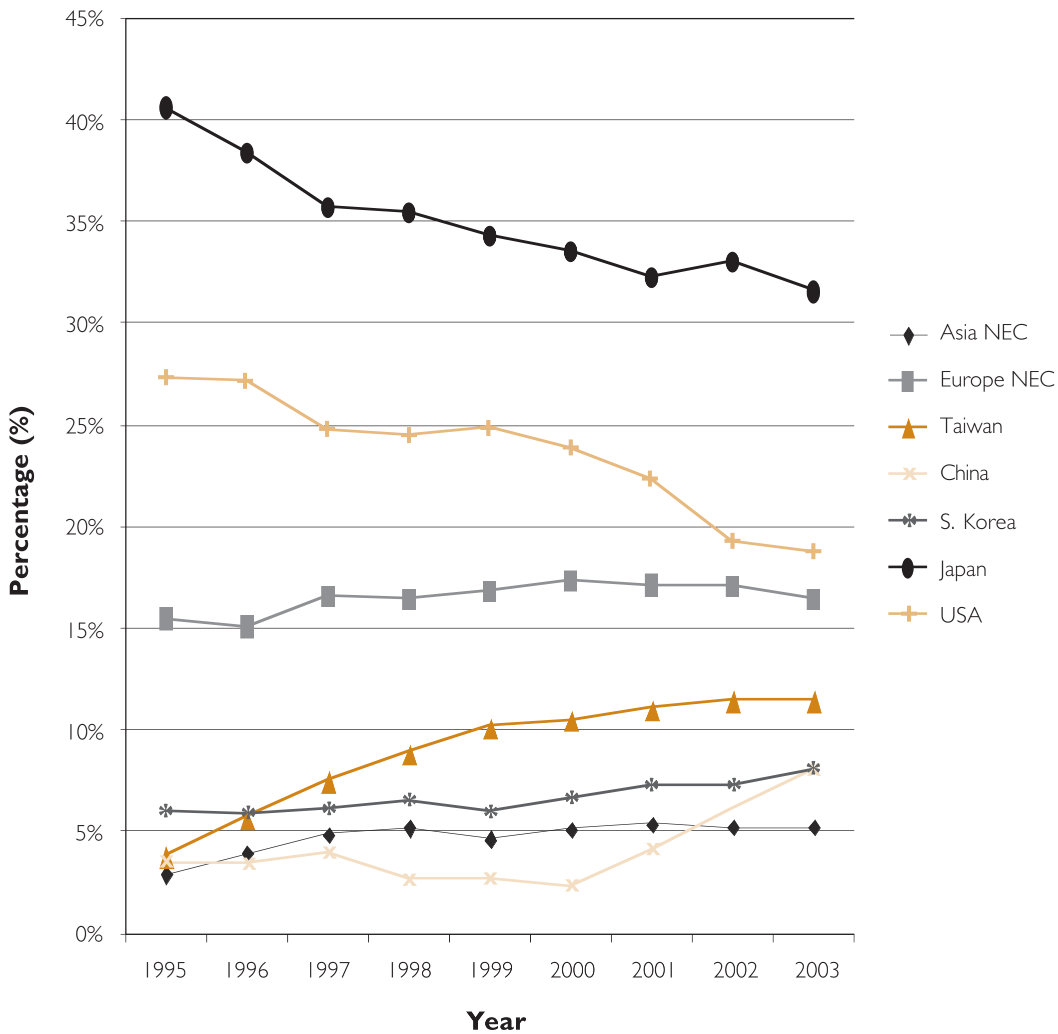
For the first two decades of the computer and semiconductor industries, large producers such as AT&T and IBM designed their own solid-state components, manufactured the majority of the capital equipment used in the production process, and utilized internally produced components in the manufacture of electronic computer systems that were leased or sold to their customers.[5] 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.

During the past twenty years, the interdependence between product design and process development has weakened in many semiconductor product segments.[6] This shift has been associated with the entry of new 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 seeking to utilize excess fabrication capacity.

Fabless semiconductor firms serve a variety of fast-growing industries, especially computers and communications, by offering innovative designs and shorter delivery times than integrated semiconductor firms. The expansion of markets for semiconductor devices enables vertically specialized semiconductor design and production firms respectively to exploit economies of specialization and scale. Specialized manufacturers can exploit production scale economies, reducing costs and expanding the range of potential end-user applications for semiconductors. Fabless-firm revenues increased from slightly less than 4% of global industry revenues in 1994 to more than 15% by 2004.

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 a limited array of semiconductor components in order to achieve lower unit costs. The design cycle for new semiconductor products also has become shorter and product lifecycles more uncertain. As a result, it is more difficult to determine 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, IDMs still combine semiconductor device design and manufacture in a single organizational entity. The advantages

FIGURE 2. Geographic Location of Semiconductor Manufacturing Capacity, 1995-2003



of integrated management of design and manufacture appear to be greatest for products at the leading edge of semiconductor technology, such as DRAMs.[7]

Increased vertical specialization in the semiconductor industry has been associated with the entry of new firms and the geographic redistribution of production capacity. Figure 2 shows the regional distribution of fabrication capacity (measured in terms of wafer starts per month)[8] during 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 is likely to continue to grow.

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 into numerous 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. The most advanced foundries are located in the Southeast Asian countries of Singapore and (especially) Taiwan. A few Taiwanese firms have opened foundries in the United 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 are more concentrated within the United States.[9] U.S. fabless semiconductor firms accounted for at least 60% of the value of orders received by the top four foundry firms (TSMC, UMC, Chartered, and SMIC) during 2000-2004. Several non-U.S. clusters of fabless firms have emerged in Israel, Canada, Taiwan, and the United Kingdom, but most of these non-U.S. fabless firms are relatively small.

A number of factors have contributed to the continued U.S. dominance of semiconductor product design. Established regional high-technology clusters in areas such as Silicon Valley, Boston's Route 128, and Austin, Texas, attract large numbers of product designers. These clusters are located near universities

TABLE 1. Fabless Firms by Country of Location, 2002

Country	Fabless Firms	Non-U.S. City	Fabless Firms
U.S.	475	Tel Aviv, Israel	14
Canada	30	Ottawa, Canada	13
Israel	29	Hsinchu, Taiwan	13
Taiwan	22	Seoul, South Korea	9
U.K.	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: R. Arensman, "Fabless Goes Global," Electronic Business, March 21, 2003.

and other research centers that produce new design techniques, design software, and engineering talent.[10]

Although we lack data to track these trends more systematically, most industry observers suggest that Southeast Asian countries will account for a growing share of global semiconductor industry design activities in the future.[11] As U.S. (especially fabless) semiconductor firms seek to collaborate more closely with the systems firms that are located in Southeast Asia, a regional or local design presence will become more 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.[12] Offshore design centers, particularly in China and India, may offer cost savings and comparable productivity in less-sophisticated design activities.[13]

Measuring Globalization of Innovation-Related Activities in Semiconductors

Indicators of Offshore Innovation-Related Activities

We use three indicators to examine trends in the offshore R&D activities of firms in the global semiconductor industry:

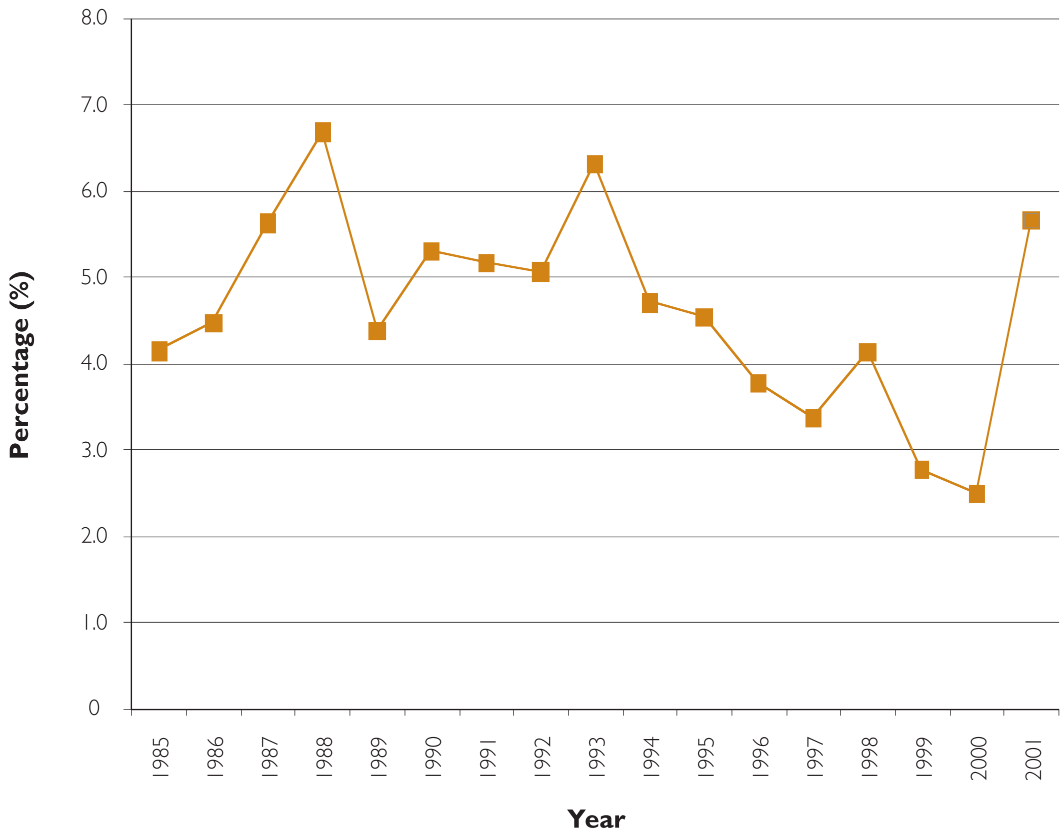
- the share of industry-funded R&D expenditures supporting offshore R&D (available only for U.S. firms) for 1985-2001;
- the number of international and domestic alliances formed by semiconductor firms during 1990-1999; and
- the site of inventive activity resulting in U.S. patents issued to U.S. and non-U.S. semiconductor firms during 1994-2004.

Each measure by itself provides an incomplete portrait of the extent of "globalization" or "non-globalization" of innovation-related activities within the semiconductor industry, but when considered together present more convincing evidence.

Industry-Funded Offshore R&D Investment

Figure 3 depicts trends in offshore R&D investment (measured as a share of industry-funded R&D spending) by U.S. manufacturers of electronic components during 1985-2001. The data in Figure 3 depict minimal change in the share of offshore R&D within total industry-funded R&D, which drops to less than 3% by 2000 from its 1985 share of more than 4%. 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 industry investment behavior.

FIGURE 3. Foreign R&D as Percentage of Industry-Funded R&D (Electronic Components), 1985–2001



The industry-level R&D investment data compiled by NSF that are the source for Figure 3 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 3, 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 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 3.

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 investment data may not include process innovation or the "tweaking" that occurs within the production facilities of IDMs. Much process innovation within manufacturing foundries relies heavily on production facility upgrades that 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 1985-2001 in reported offshore R&D investment is striking. This widely accepted measure of "globalization of innovation" indicates that U.S. semiconductor firms are in fact not expanding this portion of their offshore innovation-related activities significantly, and the offshore portion of their self-financed R&D investment remains modest, especially by comparison with other high-technology U.S. industries such as pharmaceuticals.

International Technology-Development Alliances

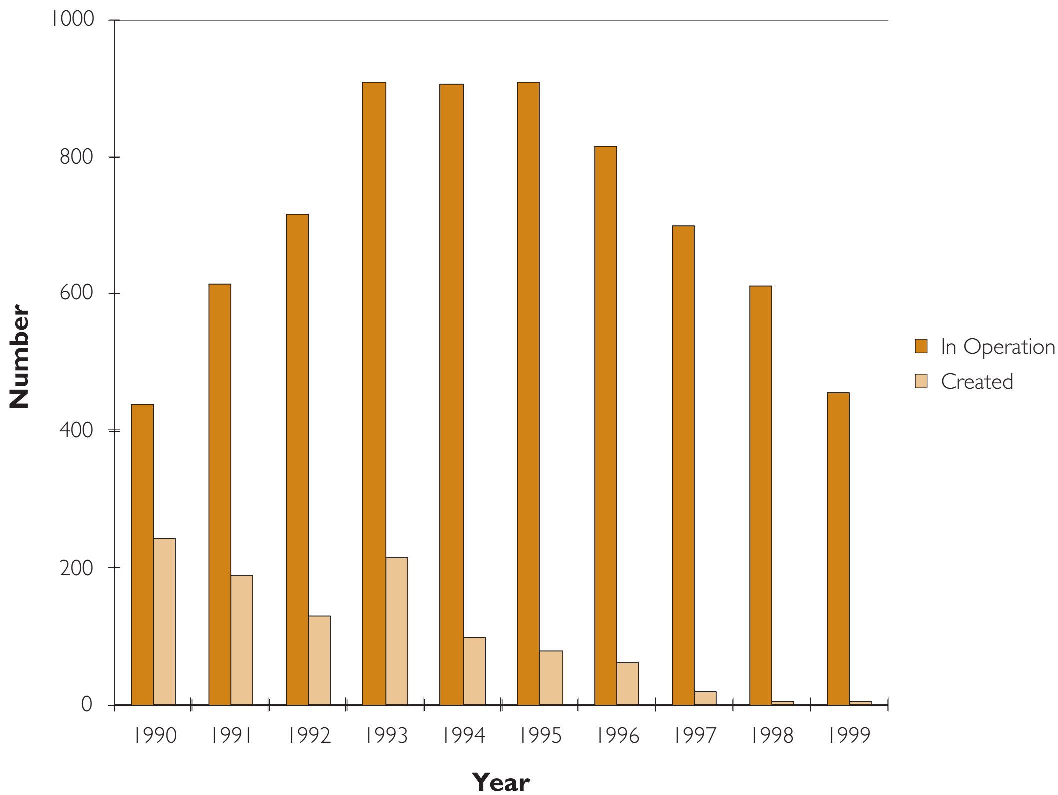
Our second indicator of globalization of innovation-related activities is the innovation-related alliances formed by U.S. and non-U.S. semiconductor firms during 1990-1999. The data that we use to track alliances in this industry cover both domestic and international alliances, and were obtained from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

The alliances in our ICE database include a diverse array of activities related to innovation and technology development in semiconductors. Some of the alliances consist of production sourcing agreements between fabless and foundry firms, while 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. Our 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 measures of their economic importance. In spite of these problems, the ICE data have some advantages. They enable us to track both the dissolution and formation of alliances, and thus provide information on the rate of new alliance formation and the number of semiconductor industry alliances in existence during our sample period.

Figure 4 displays the number of newly formed and ongoing alliances in the semiconductor industry during 1990-1999. The number of alliances in operation within the global semiconductor industry grew during the early 1990s, reached a peak during the middle of the decade, and has gradually declined since 1995 as the rate of formation of alliances has decreased. The annual "stock" of alliances in operation averaged more than 400 during 1990-1999.

The composition of alliances also changed substantially during the 1990s. Figure 5 disaggregates the "stock" of alliances in Figure 4 based on the nationality of the firms participating in the alliances. "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% of semiconductor industry alliances in 1990 to slightly more than 20% in 1999,

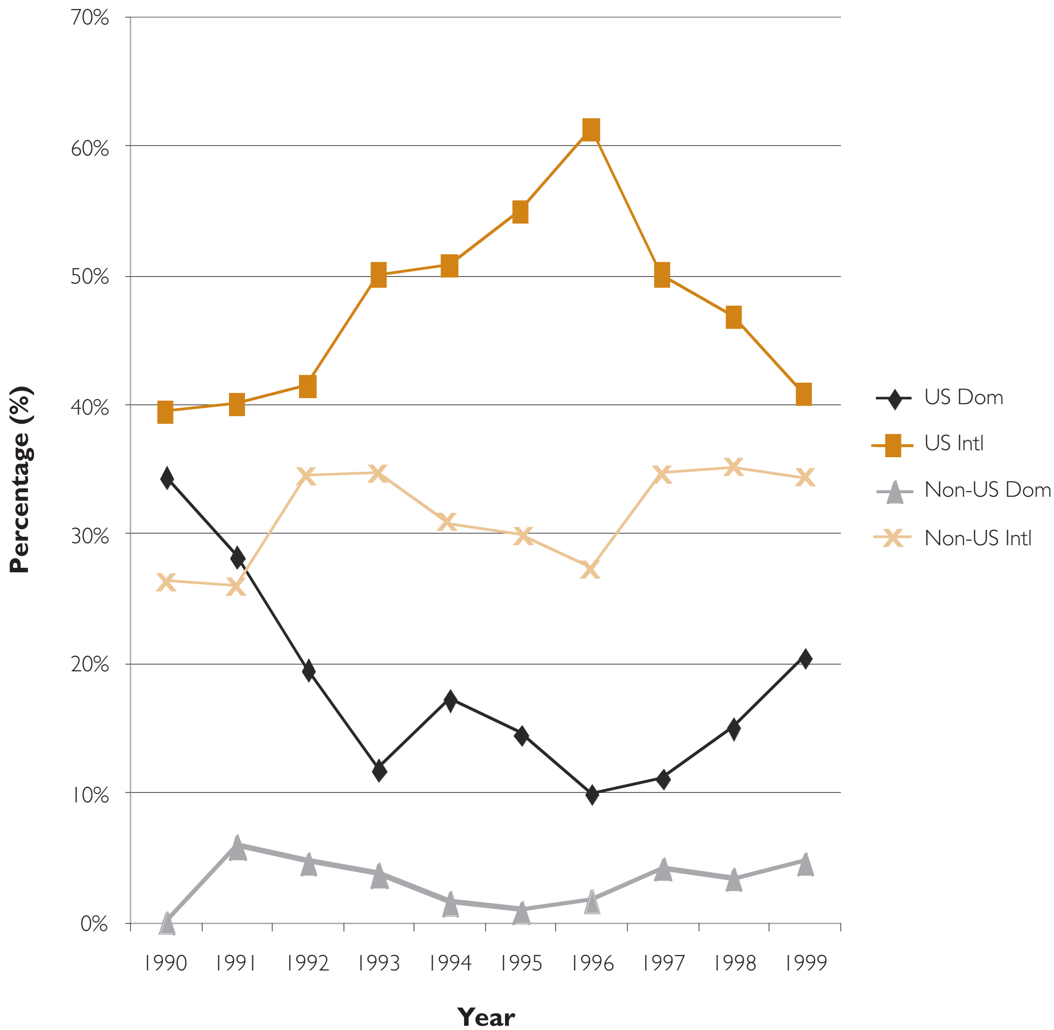
FIGURE 4. Semiconductor Industry Alliances, 1990-1999



although the 1999 share represented an increase from its low point of 10% in 1996. The share of alliances between U.S. and non-U.S. firms ("U.S. Intl") within total industry alliances is essentially unchanged in 1999 from its 1990 level, although this share grew to more than 60% by 1996 before declining to slightly more than 40% in 1999. The share of non-U.S. "domestic alliances" also declined during 1990-1999, while non-U.S. international alliances increased from slightly more that 25% of total alliances in 1990 to roughly 35% by 1999.

Taken together, Figures 4 and 5 suggest a decline in the rate of formation for R&D and technology development alliances 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. However, 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 and decline in their international alliance activities during the early and late 1990s, in contrast to 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 are using alliances to partner with

FIGURE 5. Home Region of Semiconductor Industry Alliance Participants, Alliance "Stock," 1990-1999

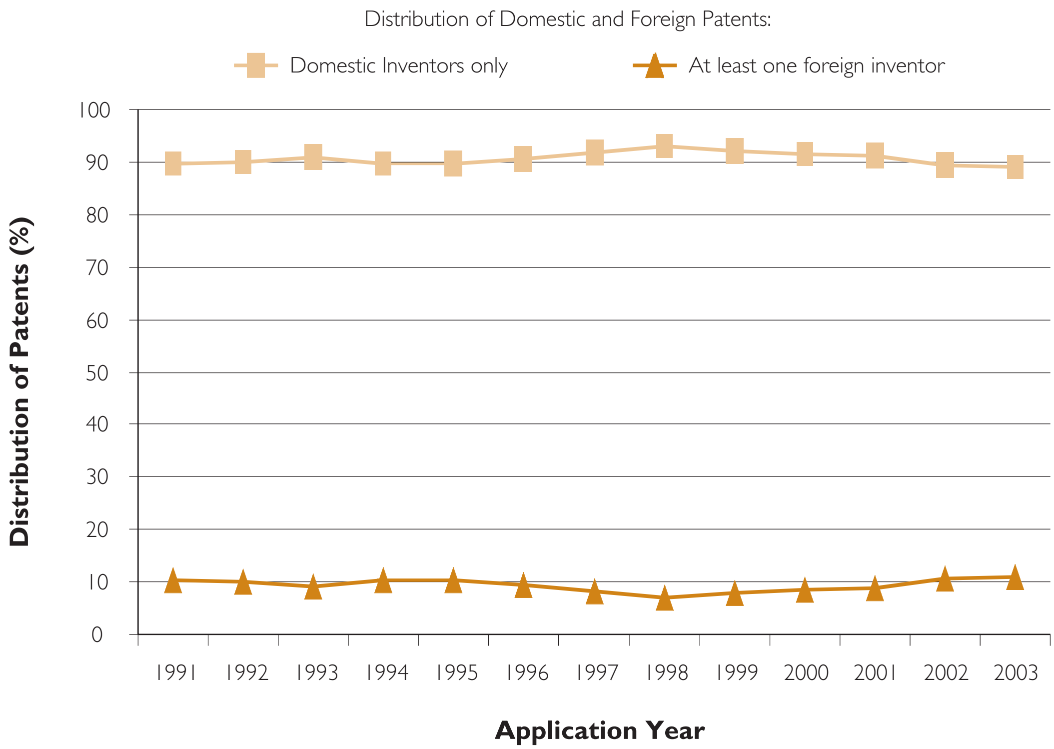


firms from other nations or regions. If anything, "globalization" through alliances therefore appears to have been more persistent and intensive for non-U.S. semiconductor firms during the latter half of the 1990s.

Patenting

Patents, our final indicator of globalization in innovation, are an input to the innovation process rather than a direct measure of the output of innovations. Nevertheless, our patent data, which are based on the semiconductor technology classification developed by the U.S. Patent & Trademark Office

FIGURE 6. Domestic & "Offshore" US-Assigned Semiconductor Patents, 1991-2003

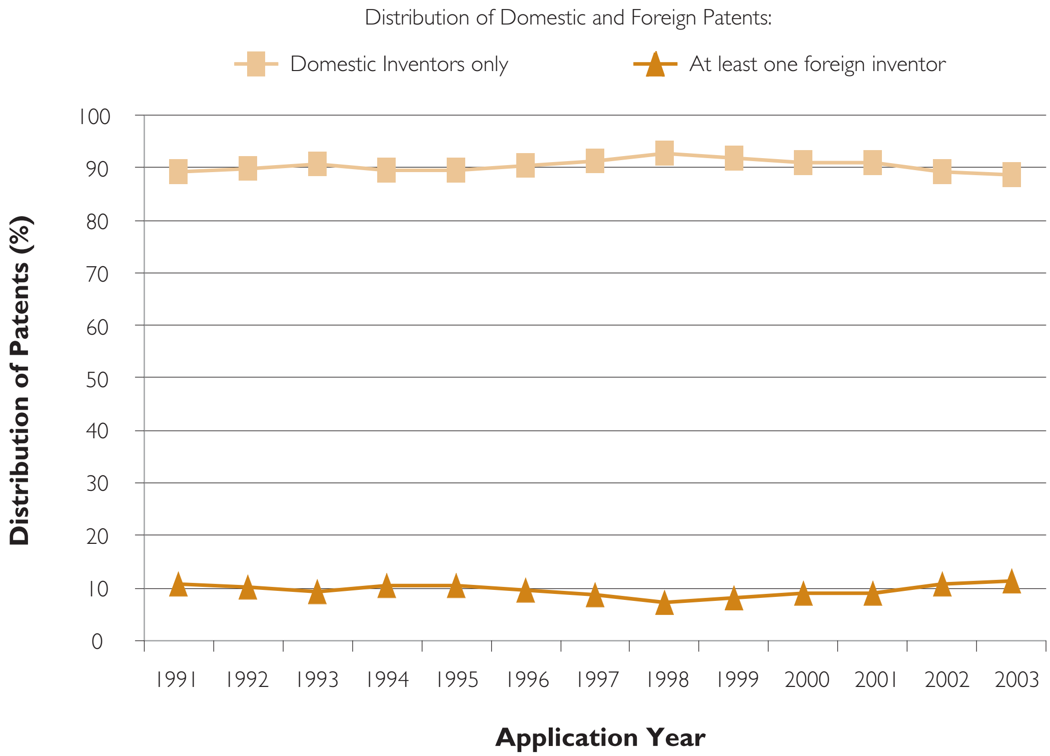


(USPTO), have several useful features. They allow us to "locate" the site of the invention that is embodied in the patent. The patent data are classified by detailed technology class, which enables us to develop measures of patenting that are specific to semiconductors. We are also able to weight our patent observations by various citation-based measures of the significance of individual patents, in order to partially control for the skewed distribution of patents by economic or technological importance.

Our empirical analysis utilizes patents assigned to 217 U.S. and non-U.S. semiconductor firms during 1991-2003 (based on year of application). This dataset includes almost 114,000 patents from more than 80 patent classes, as identified by Hall and Ziedonis and the USPTO's Office of Technology Assessment and Forecast.[14] We also collected data on citations to these patents in subsequently issued patents in all patent classes.[15]

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

FIGURE 7. Domestic & "Offshore" U.S.-Assigned Semiconductor Patents, IDM and Systems Firms, 1991–2003

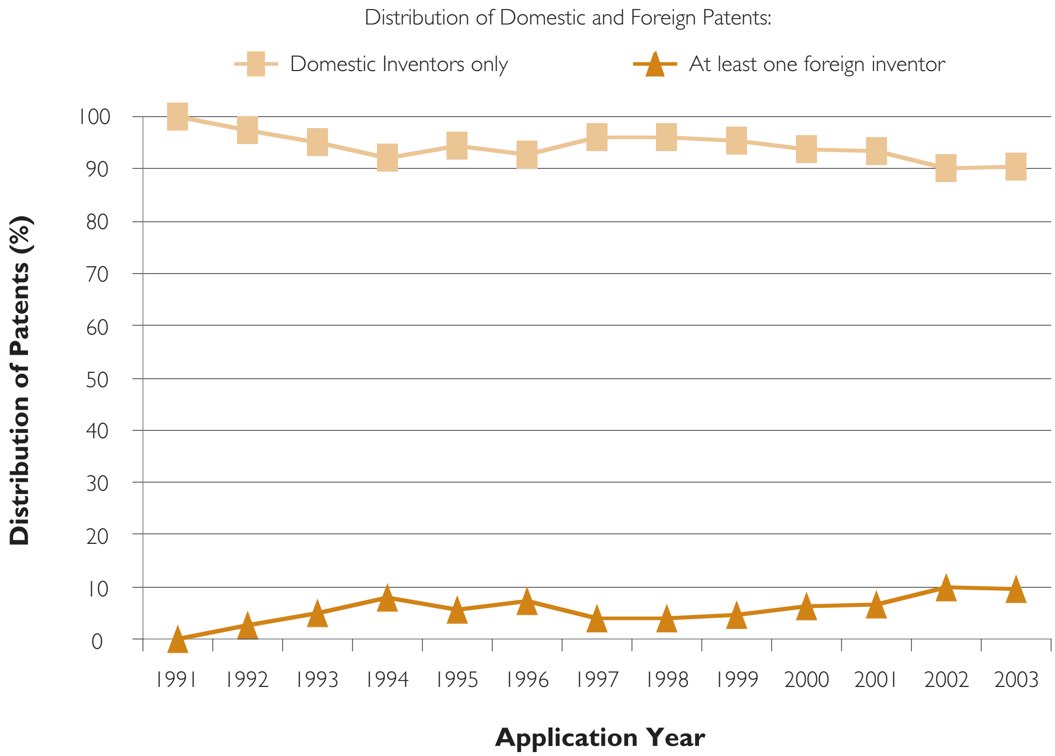


- *Domestic Patents (DO):* patents whose inventors are all located in the HQ country of the controlling company.
- *Foreign Patents (FO):* patents whose inventors are all located in countries other than the HQ country of the controlling company.
- *International Collaboration Patents (CO):* patents that have at least one inventor located in the HQ country and at least one inventor located in another country.[16]

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 patents 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,

FIGURE 8. Domestic & "Offshore" U.S.-Assigned Semiconductor Patents, Fabless Firms, 1991–2003



we include 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 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 Japanese or European patent offices.

Figure 6 displays trends during 1991-2003 in the share of all semiconductor patents assigned to U.S. firms that were created by an all-domestic inventor or inventor team and the share of semiconductor patents assigned to U.S. firms that involved at least one "offshore" inventor. 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% throughout the period. A similar lack of growth in offshore inventive activity also is apparent in Figure 7, which depicts 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 8 reveals a slight shift toward greater offshore inventive activity among fabless firms.[17] Even for this group of firms, however, patenting remains dominated by "home-country" inventive activity.

TABLE 2. Firm HQ and Location of Inventive Activity, U.S Patents

Firm HQ In	1994-2003 One Inventor Located In								
	USA	**Europe**	**Japan**	**Taiwan**	**Korea**	**Israel**	**Canada**	**Singapore**	**Others**
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%

Firm HQ In	1996-1999 One Inventor Located In								
	USA	**Europe**	**Japan**	**Taiwan**	**Korea**	**Israel**	**Canada**	**Singapore**	**Others**
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%

Firm HQ In	2000-2003 One Inventor Located In								
	USA	**Europe**	**Japan**	**Taiwan**	**Korea**	**Israel**	**Canada**	**Singapore**	**Others**
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%

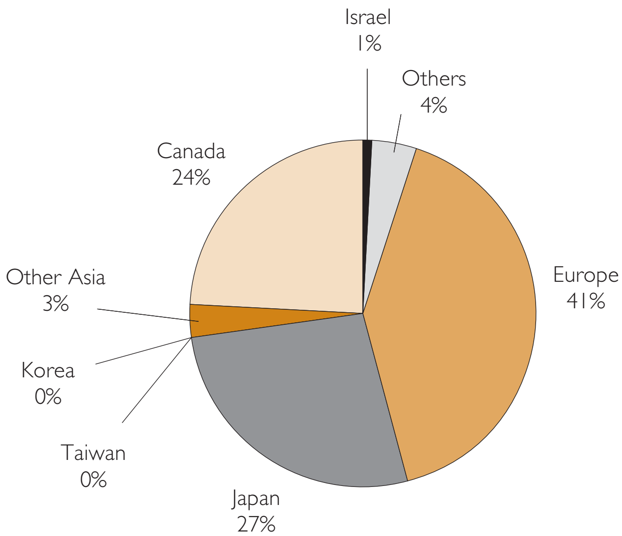
Table 2 disaggregates our patent data by "home country" and site of inventive activity for 1996-2003, as well as the 1996-1999 and 2000-2003 sub-periods. Japanese firms' inventive activity is dominated by "home-country" inventors to a greater extent than is true of either U.S. or European semiconductor firms for the 1996-2003 subperiod. Japanese inventors are listed on more than 95% of Japanese firms' U.S. patents, while U.S. inventors are listed on more than 87% of U.S. patents and European inventors appear on nearly 60% of European firms' U.S. patents. Looking at the "off-diagonal" portions of Table 2, 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% of European firms' U.S. patents, while Japanese inventors appear on less than 2%. A comparison of the two sub-periods does not reveal significant differences, although there is some indication that the "homeboundedness" of the inventive activities of European, Japanese, and Taiwanese semiconductor firms increased slightly. For all but Canadian semiconductor firms, the single most important "offshore" site for inventive activity by non-U.S. semiconductor firms is the United States. For U.S. semiconductor firms, the leading "offshore" site for inventive activity in both periods is Europe, followed closely by Japan.

Figure 9 depicts the leading locations of "offshore" inventors in the semiconductor patents assigned to U.S. firms for the 1996-1999 and 2000-2003 subperiods. This figure highlights considerable change in these locations over time and differences in the locations of the offshore inventive activity of fabless and other firms in the U.S. semiconductor industry. Canadian inventors play a more prominent role in the patenting of fabless firms than is true of IDM and systems firms, accounting for less than 4% of the offshore inventive activity of IDMs and system firms, versus more than 20% for fabless firms, in both periods. The Japanese share of fabless-firm patenting also declines between the two subperiods, perhaps reflecting the growth in electronic systems production and semiconductor component design in non-Japanese Asia (notably, Taiwan, South Korea, and Singapore). European inventors are of comparable importance for both groups of U.S. semiconductor firms (fabless firms and IDM or systems 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 (largely Singapore) for fabless firms increases more than sixfold (albeit from a modest initial level), and the "other Asia" share for IDMs and systems firms nearly doubles.

Overall, the results of our analysis of the site of inventive activity resulting in U.S. patents support the original findings of the broader analysis of patenting by firms from a broader sample of industries by Patel and Pavitt,[18] who found that large multinational firms' patenting was dominated by "home-base" inventive activity. Moreover, there is little evidence that the most "important" semiconductor patents, measured in terms of citations to them following issue, are more or less "homebound" in their origins. The trends in patenting for fabless firms suggest the possibility that the demanding requirements for close collaboration between semiconductor component designers and systems firms may be causing some shift within this semiconductor industry segment towards greater reliance on foreign inventive activity in patenting; but any such trend is very modest.

FIGURE 9. "Offshore" Invention Sites, U.S.-Assigned Semiconductor Patents, 1996–2003

Fabless Firms Offshore Sites, 1996-1999



Fabless Firms Offshore Sites, 2000-2003

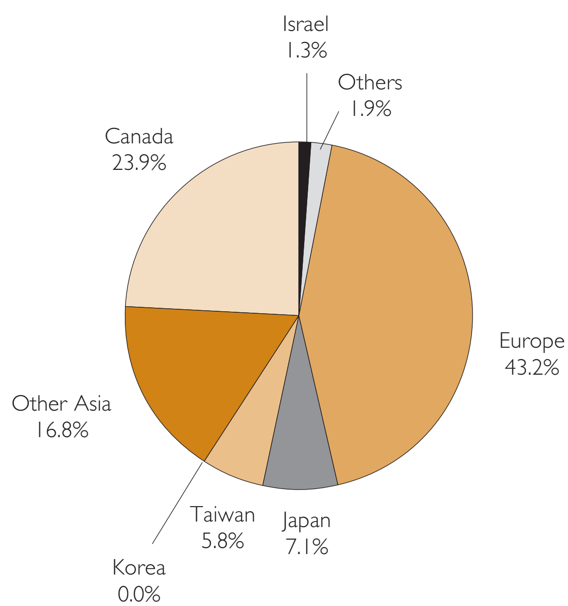
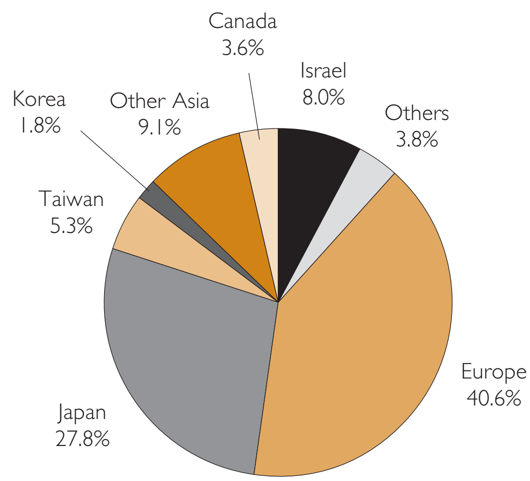
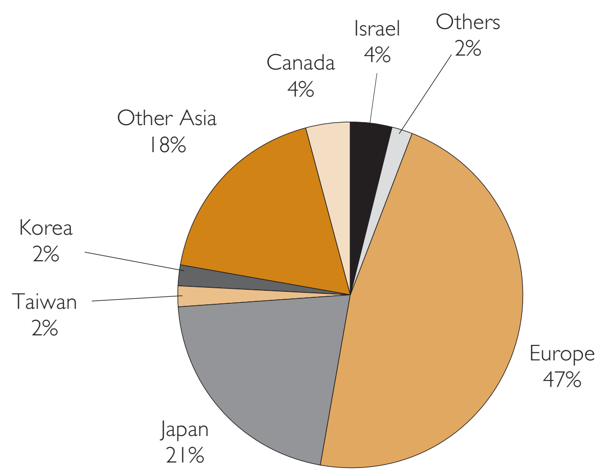


FIGURE 9. "Offshore" Invention Sites, U.S.-Assigned Semiconductor Patents, 1996–2003 *(continued)*

IDMs/Systems Firms Distribution of Offshore Sites, 1996-1999



IDMs/Systems Firms Distribution of Offshore Sites, 2000-2003



Implications for Firm Strategy and Public Policy

An earlier study of the U.S. semiconductor industry's innovative and competitive performance 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.[19] 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 altered the structure of the innovation process.

Fabless firms in particular seek to develop closer collaborative relationships with systems firms based outside of the United States. Shorter product lifecycles and the increased variety of applications that utilize semiconductor components mean that integrated device manufacturers face greater risks from swings in demand as the costs of their production facilities continue to rise. The design and (especially) 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 challenges of the 1980s that threatened the viability and very survival of the U.S. semiconductor industry, the challenges of the early 21st century for U.S. semiconductor firms stem from the need to manage this global division of labor successfully while maintaining leadership in innovation. 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 these more cost-sensitive, lower-value-added activities are shifted to offshore locations, U.S. firms have maintained their global competitiveness by developing and introducing innovative new products (e.g., personal computers and communications devices) and business models (e.g., fabless semiconductor firms). In the semiconductor industry, continued product innovation will remain central. U.S. integrated-device manufacturers must also maintain their strengths in process innovation while focusing their manufacturing strategies on a narrower range of innovative products in which they remain dominant. In other words, the strategic management of innovation becomes even more central to the competitive performance of semiconductor firms that seek to exploit the emerging global division of labor in product design and manufacturing while simultaneously maintaining strength in product and process innovation.

It is likely, for example, that U.S. integrated-device manufacturers will continue to exploit offshore sites for internal manufacturing, while simultaneously relying on "foundries" to serve a larger portion of their needs for products that are slightly behind the "bleeding edge" of technology—the so-called "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.

Interestingly, the limited restructuring of U.S. semiconductor firms' innovation-related activities that has taken place since the mid-1980s does not appear to have had negative consequences for engineering employment. A recent analysis of engineering-employment trends in the U.S. semiconductor industry found that employment and earnings growth were higher during 2000-2005 for engineers employed in the U.S. semiconductor industry than in other U.S. industries.[20] Employment growth during this period was strongest for electrical, computer hardware, and electronic engineers, but was negative for industrial engineers within the semiconductor industry. This analysis also provides 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.[21] 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" within this older cohort thus have remained out of management, which may affect their reported earnings.

In spite of the powerful forces that are shifting some design, manufacturing, and other functions to offshore locations, the location of "inventive activity" has not shifted over the time period we examine. 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 by Patel and Pavitt in an analysis of patenting by multinational firms in a broad array of industries.[22] The "non-globalization" of patenting activity seems to reflect the strong dependence of domestic inventive activity on domestic sources of fundamental research. Despite remarkable advances in the codification and global transmission of scientific research, access to such research results for purposes of inventive activity appears to remain 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: the importance of continued (and arguably, renewed) federal funding for R&D in the engineering and physical sciences in industry and universities; and 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.

The remarkable record of innovation in the U.S. semiconductor and related IT industries that spans the 1945-2006 period rested in part 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, but 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 other related industries.

The importance of market demand in the locational structure of innovation in the semiconductor industry and other high-technology industries is difficult to overstate. We have noted that the declining share of semiconductor consumption accounted for by the personal computer has been associated with the growth of new markets for semiconductor components (e.g., wireless communications 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 personal computers within the United States, as well as the low costs of accessing computer networks.[23] Federal policies will affect 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 communications networks that are likely to underpin future waves of innovation in digital communications and other devices. Federal regulatory policies also influence the incentives for the large private investments in advanced communications infrastructure that can support 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 are demanding the most advanced technologies and themselves are developing new applications of these technologies. Such markets will rest 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 utilizing semiconductor components and the entry of firms from Southeast Asia also have contributed to rapid growth in offshore manufacturing capacity within the industry, much of which remains under the control of U.S. semiconductor firms. In spite of the growth in their offshore production capacity, however, 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 reveal that the innovation-related activities of otherwise global firms in this industry remain remarkably "non-globalized," even in the face of expansion in international flows of capital and technology, far-reaching change in the structure of semiconductor product design and manufacturing, and significant shifts in the structure of demand.[24]

This characterization of U.S. semiconductor firms' innovation-related activities is supported by a number of indicators. R&D investment and alliance formations both indicate modest levels of offshore innovation-related activity. Nor do these indicators reveal a shift toward greater reliance on offshore sites for innovation-related activities. Substantial investments by U.S. semiconductor firms in "offshore" production capacity during the 1990s have not resulted in comparable shifts in the location of their inventive activities, based on patent indicators.

How can one explain these findings? It is important to highlight the retrospective nature of our indicators, which (especially in the case of patents) reflect R&D and related investments made years before the manifestation of these particular outcomes. 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-base" innovation system, especially in the product design area. "Home-base augmentation"[25] thus may be a relatively minor factor for U.S. firms' R&D investment strategies and a very significant motive for non-U.S. firms' R&D investment. 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, the hypothesized motivation for offshore R&D that receives the most unambiguous support from our analysis is the "market-demand exploitation" hypothesis of Gerybadze and Reger,[26] 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 have been reduced considerably since 1990, and it is possible that this trend has reduced their 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 Patel and Pavitt findings,[27] but these results also must be treated with some caution. As we pointed out above, 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 "non-globalized" character of U.S. semiconductor firms' innovation-related activities differ significantly from that of other semiconductor firms? Are the trends for the semiconductor industry representative of other high-technology industries, or is this industry unique? The data presented in Table 2 indicate that the "homebound" character of U.S. semiconductor firms' patenting is not unique but shared with firms headquartered in most other industrial nations, as is the "homebound" character of the process-technology development facilities that U.S. and non-U.S. IDMs and systems firms operate. The links between science and technology that underpin much of the inventive activity that is embodied in patenting retain a considerable "homebound" element, rather than operating seamlessly and frictionlessly across national boundaries.

The U.S. semiconductor industry has throughout its history maintained a position of leadership through innovation. Technological innovation within the U.S. industry rests on an infrastructure resulting from large investments made by both private firms and the federal government over decades. This infrastructure—based in firms, universities, and government research facilities—is one of the most important factors in the "homebound" nature of much of the inventive and innovative activity within the U.S. industry. Particularly as other regions of the global economy expand their investment in R&D from public and private sources, a failure to maintain the U.S. R&D infrastructure through continued investments of public and private funds could result in a much more significant offshore movement of innovation-related activities within the semiconductor industry.

Notes

1. An incomplete list of references includes: R.E. Caves, *Multinational Enterprise and Economic Analysis*, 2nd edition (New York, NY: Cambridge University Press, 1996); R.B. Freeman, "Does Globalization of the Scientific/Engineering Workforce Threaten U.S. Economic Leadership?" National Bureau of Economics Working Paper #11457, 2005, pp. 1-47; A. Gerybadze and G. Reger "Globalization of R&D: Recent Changes in the Management of Innovation in Transnational Corporations," *Research Policy*, 28/2-3 (March 1999): 251-275; W. Kuemmerle, "The Drivers of Foreign Direct Investment into Research and Development: An Empirical Investigation," *Journal of International Business Studies*, 30/1 (1999): 1-24; P. Patel and K. Pavitt, "Large Firms in the Production of the World's Technology: An Important Case of 'Nonglobalisation,'" *Journal of International Business Studies*, 22/1 (1991): 1-20; J. Thursby and M. Thursby, "Where Is the New Science in Corporate R&D," *Science*, 314 (2006): 1547-1548; R. Vernon, "International Investment and International Trade in the Product Cycle," *Quarterly Journal of Economics*, 80/2 (May 1966): 190-207.
2. 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.
3. G. Linden, C. Brown, and M. Appleyard, "The Net World Order's Influence on Global Leadership in the Semiconductor Industry," in M. Kenney and R. Florida, eds., *Locating Global Advantage: Industry Dynamics in the International Economy* (Palo Alto, CA: Stanford University Press, 2004), pp. 232-257.
4. D. Ernst, "Complexity and Internationalisation of Innovation: Why Is Chip Design Moving to Asia?" *International Journal of Innovation Management*, 9/1 (2005): 47-73.
5. E. Braun and S. MacDonald, *Revolution in Miniature: The History and Impact of Semiconductor Electronics* (Cambridge: Cambridge University Press, 1978).
6. J.T. Macher, D.C. Mowery, and D.A. Hodges, "Reversal of Fortune? The Recovery of the U.S. Semiconductor Industry," *California Management Review*, 41/1 (Fall 1998): 107-136.
7. J.T. Macher, "Technological Development and the Boundaries of the Firm: A Knowledge-Based Examination in Semiconductor Manufacturing," *Management Science*, 52/6 (June 2006): 826-843.
8. 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, and the amount of installed processing equipment. Leachman and Leachman 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. R.C. Leachman and C.H. Leachman, "Globalization of Semiconductors: Do Real Men Have Fabs, or Virtual Fabs?" in M. Kenney and R. Florida, eds., *Locating Global Advantage: Industry Dynamics in the International Economy* (Palo Alto, CA: Stanford University Press, 2004).
9. 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.
10. 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.
11. C. Brown and G. Linden, "Offshoring in the Semiconductor Industry: A Historical Perspective," in S.M. Collins and L. Brainard, eds., *Brookings Trade Forum 2005: Offshoring White-Collar Work* (Washington, D.C.: Brookings Institution Press, 2006).
12. Ernst, op. cit.
13. C. Brown and G. Linden, "Semiconductor Engineers in a Global Economy," National Academy of Engineering Workshop on the Offshoring of Engineering: Facts, Myths, Unknowns, and Implications, October 24-25, 2006, Washington, D.C.
14. Hall and Ziedonis, op. cit.

15. Patent citation data were collected with the help of the Metrics Group Division of UTEK-EKMS, an IP strategy company based in Boston.
16. Bergek and Bruzelius 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 patent-attribution problems have become more severe during the time period of this analysis. A. Bergek and M. Bruzelius, "Patents with Inventors from Different Countries: Exploring Some Methodological Issues through a Case Study," Presented at the DRUID conference, June 27-29, 2005, Copenhagen, Denmark.
17. We also analyzed the share of forward citations accounted for by the "home-invented" and "offshore participant" subsamples in our patent database. Our citation data excluded self-citations (citations to other patents held by the assignee), and yields 402,865 forward citations. We use a three-year "window" for patent citations (i.e., we limit the count of citations to those in the first three years after the year of issue of the relevant patent). Interestingly, citations are proportionate to the patent shares. In other words, there is no evidence that "home-invented" patents are cited much more intensively than those for which offshore inventors are involved.
18. Patel and Pavitt, op. cit.
19. J.T. Macher, D.C. Mowery, and D.A. Hodges, "Semiconductors," in D.C. Mowery, ed., *U.S. Industry in 2000: Studies in Competitive Performance* (Washington, D.C.: National Academy Press, 1999), pp. 245-286.
20. Brown and Linden, op. cit.
21. Brown and Linden, op. cit.
22. Patel and Pavitt, op. cit.
23. D.C. Mowery and T.S. Simcoe, "Is the Internet a U.S. Invention?—An Economic and Technological History of Computer Networking," *Research Policy*, 31/8-9 (December 2002): 1369-1387.
24. Patel and Pavitt reached a similar conclusion from their analysis of the patents of large multinational firms in a wide variety of technologies. Patel and Pavitt, op. cit.
25. Kuemmerle, op. cit.
26. Gerybadze and Reger, op. cit.
27. Patel and Pavitt, op. cit.