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Flat Panel Displays

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INTRODUCTION

This chapter focuses on the flat panel display (FPD) industry, an industry that manufactures display components for various types of electronic systems from cell phones to high-definition televisions. This is a relatively young but highly competitive and dynamic industry that got its technological start in the United States in the 1960s but quickly migrated to Japan, then to Korea and Taiwan. Despite the fact that FPDs are now manufactured almost entirely in East Asia, a number of U.S. firms (such as IBM, Corning, Applied Technologies, and Photon Dynamics) are central participants in the industry. This chapter examines changes in the structure and geographic location of the industry's innovation process since 1990 and discusses the effects of these changes on U.S. firms and workers.

One way to address these issues is to examine whether innovative activity has followed the movement of investment in FPD manufacturing. Since investment in manufacturing has been primarily in East Asia since 1990—first in Japan and then later in Korea and Taiwan—one might also expect most innovative activity to be located there. In actuality, some important innovative activity is still located outside East Asia, primarily in supplier firms in the United States and Western Europe. U.S. and European firms remain important in the industry's innovative processes, but it will be difficult for them to remain so unless they work closely with the manufacturers in East Asia. Several U.S. firms have done this and have remained, as a result, at the center of the innovation process. A major implication is that public policy should not punish U.S. firms for their efforts to follow the action in globalizing industries like this one.

BACKGROUND INFORMATION ON THE INDUSTRY

In 2005, the total value of FPD[1] sales worldwide was $65.25 billion (see Figure 1). Liquid crystal displays (LCDs) accounted for over 95 percent of FPD sales by value; thin-film transistor (TFT) LCDs accounted for over 90 percent of LCD sales; and *large-sized* TFT LCDs accounted for about 75 percent of the value of TFT LCD sales.[2] The unit volume of large-sized TFT LCD panels in 2004 was 138.5 million displays. The unit volume of small- and medium-sized LCDs in that year was around 650 million (Young, 2005). The average annual growth rate from 1990 to 2005 in the real value of FPD sales was 23 percent. Real growth rates for TFT LCD sales are likely to be somewhat higher than those for FPDs.

Demand for TFT LCDs is a function of the demand for a wide variety of products, including, among others, televisions, personal computers, PDAs, camcorders, cell phones, and digital cameras (see Figure 2). The market for TFT LCDs and other FPDs became larger and increasingly diversified as the consumer electronics market moved toward digital and high-definition televisions and portable digital devices and as the size and quality of TFT LCDs increased.

Innovations in process technology along with vigorous competition permitted consumers to benefit from steadily declining prices over time. For example, prices of TFT LCDs declined with each successive generation of production equipment. Every time the glass substrate size for processing displays increased, a new generation of production equipment was created to match that size. With the entry of Korean and Taiwanese firms into the market, the demand for TFT LCDs increased in all markets where thinness and low power consumption were valued by consumers.

The potential market for FPDs is enormous. About 780 million cell phones were sold globally in 2005; 176 million TV sets; 145 million desktop personal computers; 62 million notebook computers; 9 million Personal Digital Assistants (PDAs); 10 million camcorders; 50 million MP3 players; and 85 million digital cameras.[3] And yet, while TFT LCDs accounted for almost all notebook computer displays, camcorder viewfinders, PDA displays, and handheld TVs in 2005, they accounted for only around 60 percent of computer monitors and 10 percent of televisions. Until recently, most cell phones used Super Twisted Nematic (STN)

[1]The term flat panel display encompasses a variety of display technologies, including LCDs, plasma displays, organic light-emitting diodes, and electroluminescent displays. Many of the statistics collected about the industry focus on the largest segment of the flat panel display market—LCDs. This chapter focuses mainly on LCDs.

[2]An LCD is a thin, flat display device made up of any number of pixels arrayed in front of a light source or reflector. See http://en.wikipedia.org/wiki/Liquid_crystal_display for details. A color filter is required for color displays and, since the mid 1990s, most LCDs sold use a multiplexed active-matrix method of addressing the pixels that depends on the deposition of very small TFTs on the bottom glass panel of the device. See http://en.wikipedia.org/wiki/TFT_LCD. A large-sized panel is 10 inches or more, measured diagonally. Small- and medium-sized panels are less than 10 inches.

[3]Various business press sources. The estimate for PDAs is for 2004.

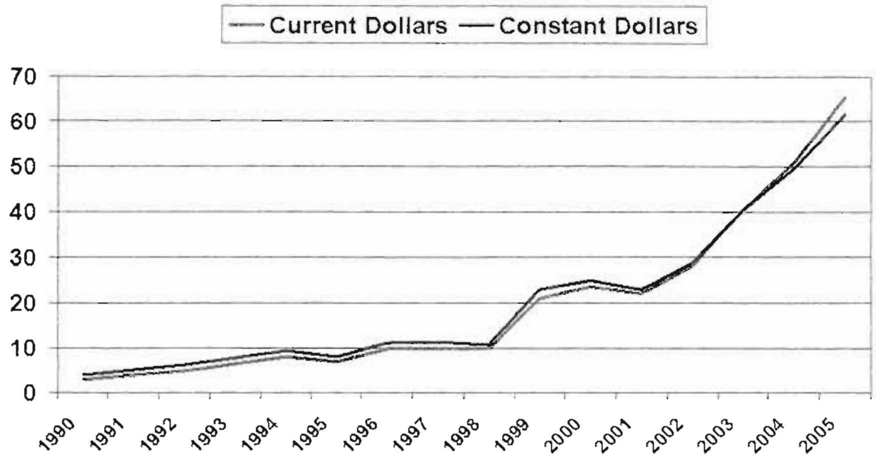

FIGURE 1 Global flat panel display revenues, 1990-2005 (current and constant 2003 dollars).
NOTE: The statistics in the figure include revenues for a variety of FPD products including LCDs, plasma displays, electroluminescent displays, and organic light-emitting diodes.
SOURCE: DisplaySearch.

LCDs because of their lower price. In 2005, however, 47 percent of cell phones had TFT LCD displays, up from 30 percent the previous year (*Softpedia News*, 2005). Even in those display markets where TFT LCDs competed with alternative technologies, growth rates were impressive. For example, in 2005, sales of LCD

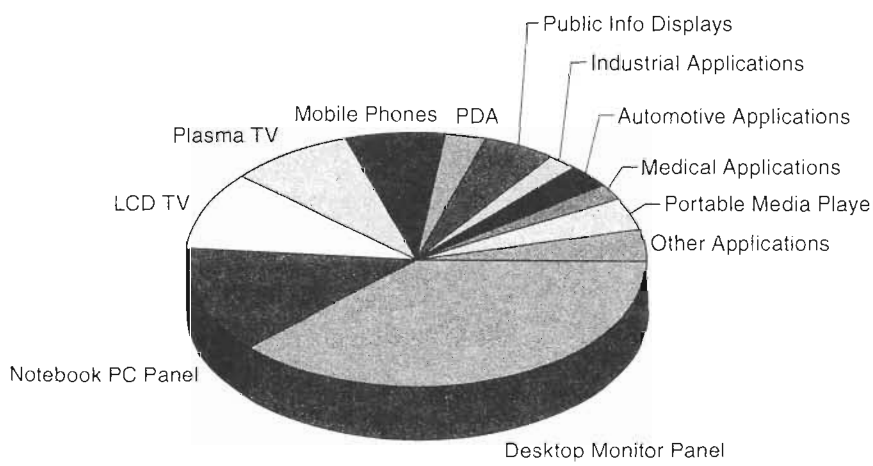

FIGURE 2 Global flat panel display sales by application, 2005. SOURCE: Frost and Sullivan, http://www.frost.com/prod/servlet/cio/FA1F-01-02-01-01/chart2.1.gif.

TVs grew to over 17 million units, up from 181,000 in 2000 (Cantrell, 2005). Figure 2 shows global sales of FPDs in 2005 by application.

Display size was initially a major constraint on demand for TFT LCDs. In the early 1980s, when the maximum size of TFT LCDs was 2 to 3 inches (measured diagonally), sales were limited to handheld TVs and camcorder viewfinders. In the late 1980s, when the maximum size was 13 inches and prices were still relatively high, computer monitor sales were limited primarily to displays for expensive notebook computers. Most notebook computers had passive-matrix[4] STN LCD displays until the price of TFT LCDs came down sufficiently to attract buyers. By the late 1990s, high-quality TFT LCD monitors for computers were being produced in high volume and prices had declined to the point where they were competitive in the marketplace with cathode ray tube (CRT) monitors.

By 2005, when the maximum size of TFT LCDs that could be produced in high-volume factories was over 40 inches, the main constraint on sales was price and quality relative to alternative similarly sized computer and TV displays, including plasma display panels (PDPs)[5] included in the FPD revenues discussed earlier. By 2005, TFT LCDs were competing successfully in television markets with 42-inch or smaller CRT-based televisions and PDPs. Given the previous price declines in smaller TFT LCDs, however, it was clear that TFT LCDs would soon be competing successfully in the larger screen sizes as well.

PATTERNS OF INVESTMENT IN MANUFACTURING

In 1996, over 95 percent of all TFT LCDs produced globally were made in Japan. In 2005, less than 11 percent were made there; the top two production locations were Korea and Taiwan (see Figure 3), each producing roughly 40 percent of global supply. The change over time in the location of TFT LCD production was a result of a sequence of investment decisions on the part of major firms in the three countries. Japan was the dominant production site until 2001, when Korean firms took the lead. Taiwanese production accomplished the same in 2002 but remained a bit below Korean production in 2002 and 2003. By 2004, the Koreans and Taiwanese were running neck and neck. Whereas the Koreans

[4]A passive-matrix display is one in which each pixel must retain its state between screen refreshes without the benefit of a steady electrical charge. Pixels in passive-matrix displays are addressed via row and column drivers. TFT LCDs are active-matrix displays because a transistor associated with each pixel holds the steady charge that is lacking in an STN LCD. A key advantage of active-matrix displays over passive-matrix displays is that it is not necessary to address each pixel via row and column drivers during each screen refresh. Only those pixels that need to change are addressed during a refresh. This generally permits active-matrix displays to have faster response times than passive-matrix displays.

[5]A PDP is an emissive FPD in which visible light is generated by phosphors excited by a plasma discharge between two panels of glass.

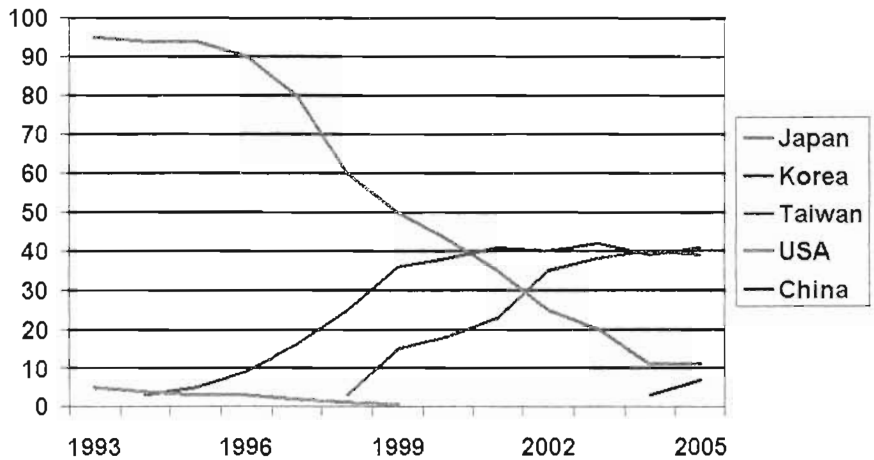

FIGURE 3 Production shares of FTF LCDs by location, 1993-2004 (percentages). SOURCE: Murtha et al. (2001).

began to produce TFT LCDs in high volume around 1995. the Taiwanese did not begin to do so until 1998.

The main reasons for this shift in production within East Asia were lower engineering and labor costs in Korea and Taiwan and the ability of first Korean and then Taiwanese firms to raise the large amounts of capital needed for investing in state-of-the-art fabrication facilities. It is important to note that most Japanese firms were not able to do this after the beginning of the bubble economy in 1991.[6] This provided a window of opportunity for the entry of Korean firms in the mid-1990s. Similarly, a window of opportunity was created for Taiwanese firms in the wake of the Asia Crisis of 1997-1998, as Korean firms temporarily experienced difficulties in financing new plants.

The ownership of production was similar to the location of production with some notable exceptions. Some of the production (less than one-fourth) located in Japan in the mid-1990s was owned by IBM through its joint venture with Toshiba (Display Technologies, Inc.). Some of the production (about one-fourth) located in Korea in the late 1990s was owned by Philips (a European firm) in its joint venture with LG (LG Philips Displays). After 2000, Sony also owned some of the

[6]After the collapse of the Japanese stock market in 1990 and a major decline in the value of real estate, Japanese banks suffered from a shortage of capital. Since many loans to small businesses were backed by property and small business loans constituted more than a majority of total loans, the entire banking system began to look shaky after 1990. Financial regulators failed to force the banks to write off their bad loans, so bank depositors began to look elsewhere for places to invest their capital and corporate borrowers began to look to overseas capital markets for loans (see Hutchison, 1998; Wood, 1992).

TABLE 1 Major TFT LCD Manufacturers by Location, 2005

Japan	Korea	Taiwan	U.S.	China
Sharp	• Samsung • LG Philips Display • Sony-Samsung LCD	• AU Optronics • Chi Mei Optoelectronics • HannStar • Quanta Display • Chunghwa Picture Tubes	None	• Beijing Orient Electronics • SVA-NEC

production in Korea through its joint venture with Samsung (S-LCD). Japanese firms provided some of the capital and technology for new entrants in Taiwan and China. They did this in order to have access to dependable supply sources of flat panels so that they would be able to compete with low-cost producers in Japan (such as Sharp) and Korea in end-user markets for computers and televisions. Taiwanese firms supplied assembled displays to Japanese firms on an original equipment manufacturer basis. Table 1 provides a list of the largest producers of TFT LCDs in 2005.

TFT-LCD Manufacturing

TFT LCD manufacturing is technically challenging, expensive, and risky. The seventh generation of TFT LCD fabrication plants required an investment of between $1.5 billion and $2 billion per plant. Because of learning-curve economies (dynamic economies of scale) in TFT LCD production, the price for any given size of display declined over time, just as it did for integrated circuits (ICs). But the competition among display firms was so intense that it was not always possible to enjoy the profits that are sometimes connected with learning-curve economies, hence the risk of making large investments with limited payoffs.

The technology for manufacturing TFT LCDs is quite complex, bearing many similarities to that for ICs. Both TFT LCD and IC production require advanced clean rooms, advanced lithography equipment, chemical or physical vapor deposition equipment, specialized testing equipment, and robotic handling equipment. TFT LCDs, like ICs, require many process steps; an error at any step may produce a faulty device. TFT LCD and IC production is highly capital-intensive, and extensive training is required for clean-room production workers and, even after a factory is producing at full capacity, a large team of production engineers must be on hand to diagnose and fix production problems. The proportion of engineers to production workers increases as one moves from generation to generation (as does the necessity to employ automated handling and conveyance technologies) because of the increasing difficulty of maintaining high yields and throughput.

As the glass substrate size increased in TFT LCD production (see Figure 4), some physical properties changed, thus creating new challenges for equipment manufacturers. For example, large glass substrates required special handling technologies because of the tendency of glass to sag when transported horizontally. Photolithography equipment had to be updated to be capable of transferring designs onto the larger and larger substrates. Filling the LCD cells with liquid crystal materials became more challenging as the cell and module size increased.

One important difference between TFT LCDs and ICs is that ICs are always shrinking in size in order to achieve a greater number of chips per silicon wafer and to speed the performance of the chip itself. In contrast, a significant portion of the global market for TFT LCDs tends to shift toward larger-sized displays (e.g., for computer monitors and TVs) while the demand for smaller displays (e.g., for cell phones) also has tended to grow rapidly, so the only way to reduce average unit costs is by increasing yields and by reducing defects on larger and larger glass substrates—the large sheets of glass on which multiple display panels are processed (see Figure 4).

This episodically requires a shift to the next generation of production technology, new tools and handling equipment geared to the larger substrates, and manufacturers to have flexible strategies with regard to the production of a variety of display sizes. Figure 4 shows that there have been six generational shifts between 1991 and 2005, so the average time between shifts has been 2.3 years. While the IC industry also has gone through transitions to larger wafer sizes (the latest being from 200- to 300-mm-diameter wafers), these transitions are

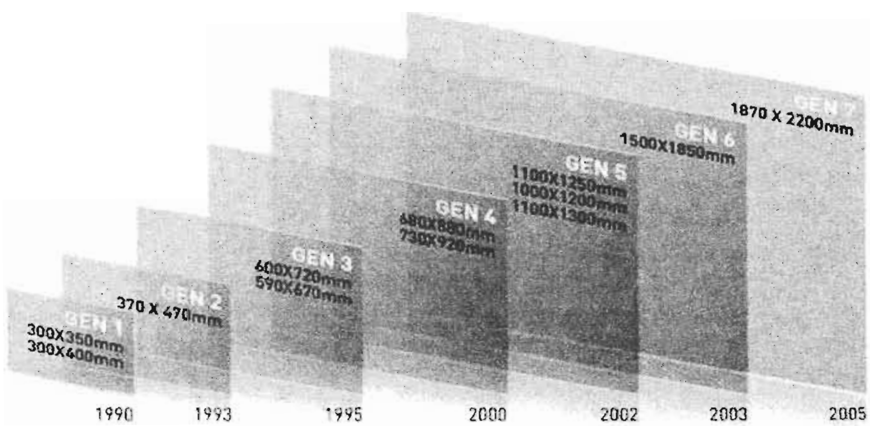

FIGURE 4 Glass substrates, first through seventh generation. SOURCE: Samsung Corning Precision, http://www.scp.samsung.com/content/en/product/generation.asp.

less frequent and ICs of a given type generally do not increase in size over time (rather they tend to shrink).

Firm Strategies

The strategy for manufacturers of TFT LCDs consists mainly of deciding if and when to invest in the construction of a new fabrication facility. Along with the decision to invest in a new line comes the even more important decision of whether to move to the next generation of substrates (see Figure 4). It is a risky decision for a number of reasons: (1) there is always uncertainty about the future demand for TFT LCDs of various sizes, (2) there is uncertainty about how many competitors will match the investment and when (hence uncertainty about future supply), (3) there are uncertainties about both product and process technologies, and (4) there are uncertainties about how well the firm itself will be able to execute its selected strategy.

Product technologies are uncertain because of the potential competition from alternative display technologies. For example, it was not clear that LCD televisions would be able to compete with CRT-based televisions and PDPs in the market for digital televisions until fifth-generation TFT LCD plants were built. Not only was there the question of relative price, there was also a question of relative quality of displays and the premium that consumers would be willing to pay for higher quality.

Process technologies are uncertain because of the problems connected with scaling up equipment and altering handling systems for each generation of substrates. In the move from second- to third-generation substrates, for example, it was necessary to move to new types of conveyor systems and automated guided vehicles to transfer partially processed glass substrates from one machine to another on the factory floor. This was done to reduce both breakage and particle contamination rates.

Besides having to deal with technological and other uncertainties, manufacturers have to decide which suppliers to work with. This can be crucial because of the need to ramp up production quickly in order to exploit whatever temporary advantages might accrue to early investors. Suppliers can fail manufacturers in a number of ways: Materials suppliers might not be able to provide key inputs at the right time; equipment suppliers might not be able to deliver or maintain equipment that is crucial to raising yield and throughput. Because of the extreme time pressures in this industry, most manufacturers work with established suppliers who have extensive experience with high-volume TFT LCD manufacturing. Only if a new and inexperienced supplier has a very important technological edge will a manufacturer be willing to work with them.

Consider the strategies selected by Japan's pioneer TFT LCD manufacturer, Sharp, in the early 1980s. Sharp invested earlier than other Japanese firms in the first generation of TFT LCD plants mainly because management believed that not having an internal source for CRTs had hurt Sharp's ability to compete with other Japanese firms in the television business. As an early producer of handheld TVs and calculators, Sharp saw a bright future for other devices that required information displays. Sharp management accepted the risk of investing in an unproven display technology because they felt they had no other choice.

Sharp initially worked with only a few external suppliers and tried to develop its own manufacturing equipment. When the IBM-Toshiba joint venture, DTI, built a third-generation plant in Japan that outperformed Sharp's earlier-generation plants, it did so by relying more than Sharp had done on external suppliers. As production moved from Japan to Korea to Taiwan, firms in the other East Asian countries generally became increasingly dependent on external suppliers, mainly because they lacked the ability to develop quickly all the necessary capabilities in-house. In addition, they moved some of the more labor-intensive processes, such as module assembly, to lower-wage locations, including China.

Third-generation plants were considerably more automated than earlier-generation plants, so external equipment firms that could work with manufacturers to perfect their automation systems had an opportunity to become key participants in the industry. (We will later see how this approach worked for two U.S. firms—Applied Materials and Photon Dynamics.)

During the bubble economy period in Japan, most Japanese firms were unable to invest in new plants. Instead they retrofitted their old plants to produce higher value-added products like low-temperature polysilicon TFT LCDs, which were mainly used for small displays such as those used in cell phones. Later several of these firms moved their display operations to Taiwan and China through foreign investment and technology transfers.

The decision of the Taiwanese firms to invest in fifth-generation plants when Korean firms were investing in sixth- and seventh-generation plants requires some explanation. The logic of entry via the latest generation may not have held for Taiwanese entry because of the ability of the Taiwanese to find other ways to become cost-effective manufacturers. Being the first mover to a new production technology can be quite expensive, especially if the rest of the industry is not ready to make the jump. Nevertheless, since their entry in the late 1990s, Taiwanese firms have invested in latest-generation plants as soon as they were able.

The development and introduction of each successive production generation occurred in a variety of locations, but importantly the successful integration of each generation of production equipment depended on investment in high-volume production. This meant that developers of equipment had to work with whatever firms had decided to be early adopters of the latest generation in order to remain competitive. Similarly, firms that supplied key inputs, like glass substrates and color filters, also had to do this.

To be more specific, the development of lithographic equipment occurred primarily in Japan, the United States, and Western Europe, even though installation and testing of that equipment was primarily in East Asia from the 1980s onward. Similarly, liquid crystal materials were developed and fabricated primarily in Western Europe and then sold to East Asian producers. Chemical vapor deposition (CVD) equipment was developed primarily in the United States and Western Europe. Testing equipment was developed mainly in Japan and the United States. In short, new materials and equipment did not have to be developed in the same countries that invested in manufacturing, but firms that supplied the manufacturers had to work closely with them to remain competitive.

Unlike the semiconductor industry, where design and manufacturing became less integrated over time (in fabless firms and foundries), no such vertical disintegration of that part of the value chain occurred in the FPD industry. However, in other parts of the value chain it was possible for some disintegration to occur, particularly between the glass-processing phase and the final assembly phase of production.

Materials and equipment suppliers became more important over time because of the time pressures created by the rapid changeover from one generation of production technology to the next. Korean and Taiwanese firms were generally unable to emulate Japanese leaders, mainly Sharp and NEC, in building their own production equipment; instead, they had to rely on external suppliers to a greater extent.

THE STRUCTURE OF INNOVATION

Innovation in this industry (as in other manufacturing industries) occurs in both the design of new products and the refining of manufacturing processes. For example, as TFT LCDs started penetrating the market for televisions, panels had to be improved to meet the need for wider viewing angles than is necessary for displays in notebook and desktop computers. A key innovation was "in-plane switching" technology because it increased viewing angles along with contrast ratios and brightness of displays. The response times required for real-time video in video games and television also required innovations in product technology. In 2001, NEC developed its "feed forward" technology to speed up response times for televisions. Various types of "overdrive" or "response time compensation" technology were developed by Samsung, LG Philips, CMO, BenQ, and ViewSonic for their displays.[7] An example of a major recent innovation in process technology was the invention of "one drop fill"—a new way of inserting liquid crystal material between the two processed glass plates of a TFT LCD (Kamiya et al., 2001). With every increase in the size of substrates came a demand for new processing and handling machines.

While manufacturers must innovate both process and process technologies, they are often helped by suppliers. When suppliers who are not manufacturers themselves provide new materials or processing equipment, they must work

[7] "Advanced Technology," *TFT Central*, http://www.tftcentral.co.uk/advanced.htm.

closely with manufacturers to ensure that the materials and equipment will meet the needs of their customers. The intense competition in TFT LCD end-user markets from other manufacturers and from alternative technologies means that manufacturers must bring new plants online as quickly and cheaply as possible, and to do this they increasingly turn to external suppliers.

Patenting activity can be used as a crude indicator of innovation. Location of patenting activity in the TFT LCD industry tends to follow investment in manufacturing with a lag (see Figure 5). For example, the five largest holders of U.S. LCD patents as of 2005 were Sharp, LG Philips, Canon, Hitachi, and Seiko-Epson. LG Philips's U.S. patenting activity began in 2000 just as Sharp's patenting activity declined. Samsung's patenting activity was markedly lower than that of LG Philips but it also took a turn upward from 1995 onward. Between 2000 and 2005, the four major Taiwanese firms (AU Optronics, Chungwha Picture Tubes, Chi Mei Optoelectronics, and HannStar Display) successfully filed for LCD patents in the United States but the total patents granted were considerably fewer in number than those held by Japanese and Korean firms (see Figure 6).

U.S. firms accounted for a decreasing percentage of total patents between 1969 and 2005 (see Figure 6). This figure was generated by counting the annual number of U.S. patents for which patent holders were either U.S.-owned firms or U.S.-located laboratories and comparing that number to the total. Even before IBM decided to exit the TFT LCD market as a manufacturer, U.S. firms were not keeping up with the increased patenting activity of foreign firms.

Because of rapid technological change, the role of tacit knowledge, and the importance of proximity to physical production, much of the innovative

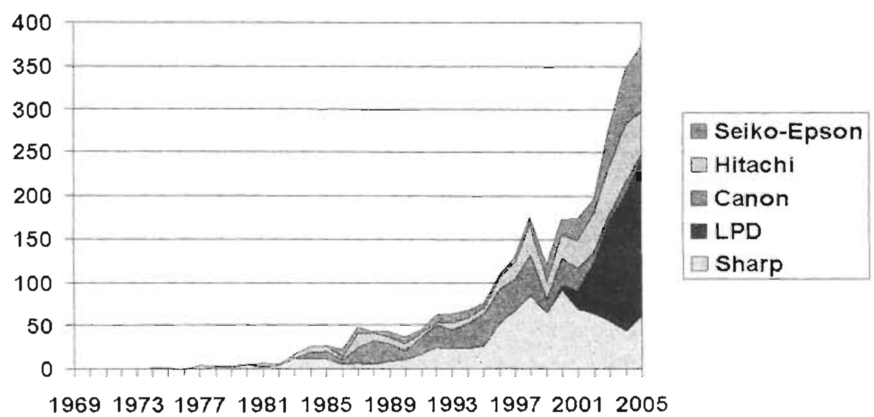

FIGURE 5 U.S. LCD patents granted annually to the top five patent holders, 1969-2005. SOURCE: U.S. Patent Office, http://www/uspto.gov/go/taf/tecasga/349_tor.htm.

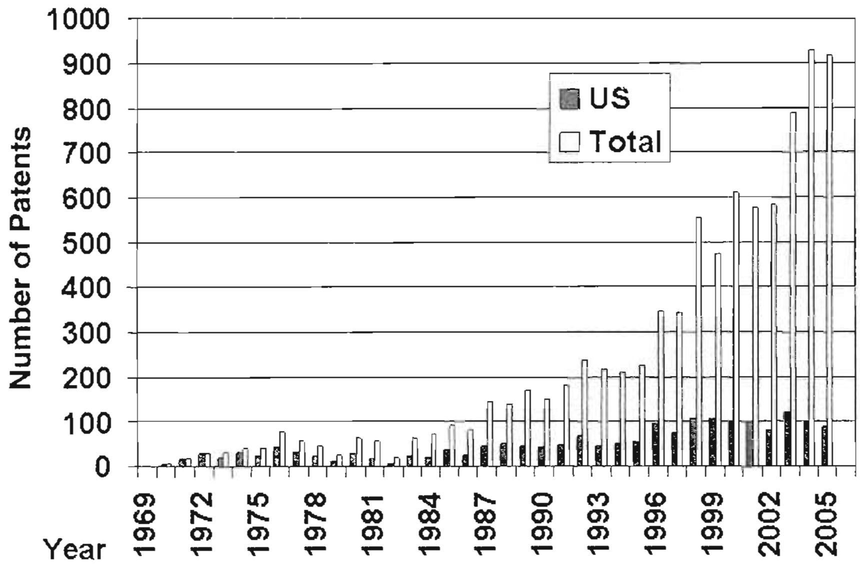

FIGURE 6 Number of LCD patents issued to U.S. firms or laboratories compared with total number of patents, 1969-2005. SOURCE: U.S. Patent Office, http://www/uspto.gov/go/taf/tecasga/349_tor.htm.

activity takes place within the manufacturing firms themselves and particularly within their associated laboratories. In East Asia, most scientists and engineers employed by domestic firms are nationals of the home country. There is very little research and development (R&D) done by these firms outside their home countries. Other than Sharp's laboratory in Camas, Washington, no major display research laboratory was established by an Asian firm in the United States. This contrasts markedly with the nationality and location of scientists and engineers employed by U.S. and European firms. IBM Japan operated an important display laboratory in Yamato; Philips acquired the laboratories of Hosiden in Japan and then worked in collaboration with LG in Korea after the joint venture was established. Many members of the top management of Korean and Taiwanese firms were previously employed by U.S. or European firms and received graduate training in U.S. and European universities. For example, the head of Samsung's TFT LCD operations was Jun Souk, who had previously worked for IBM.

Some important innovations occur in government and university laboratories or in supplier firms and in collaborations between suppliers and manufacturing firms. To demonstrate this, I turn to a discussion of the historical importance of U.S. firms as both suppliers and manufacturers in the TFT LCD industry.

U.S. Participants in the Industry

The story of TFT LCD manufacturing in the United States began in the late 1960s with a number of important successes in the research efforts of major firms like RCA, Westinghouse, Exxon, Xerox, AT&T, and IBM. However, none of these firms (except IBM) decided to invest in volume manufacturing of TFT LCDs. IBM decided in 1986 to invest in high-volume production only in Japan and only in a joint venture with Toshiba. During the 1980s, in the wake of the high dollar and Japanese successes in semiconductors, U.S. firms (other than IBM) decided not to invest in TFT LCD manufacturing. In contrast, all the major Japanese electronics firms had invested in high-volume TFT LCD manufacturing by the late 1980s.

Nevertheless, a number of U.S. firms decided to participate in the industry, most notably IBM, Corning, Applied Materials, and Photon Dynamics (to name the four important firms). These firms remained key players in the market thanks to their ability and willingness to acquire knowledge by working collaboratively with manufacturers outside the United States.

All U.S. manufacturers of TFT LCDs other than IBM were relatively small, niche producers.[8] These firms engaged in a variety of efforts to catch up with the Japanese leaders, some of which involved help from the U.S. government, particularly the Advanced Research Projects Agency of the Department of Defense. They failed mostly because U.S. governmental policies made it difficult for firms receiving government funds to work closely with manufacturers in Asia. But government policy was not solely to blame for this. Most U.S. firms had not grasped the essence of the problem: To succeed in entering the industry at this stage, they had to work with partners experienced in high-volume production.[9] Firms that understood this—IBM, Corning, Applied Materials, and Photon Dynamics—were successful, as discussed next.

IBM

In 1986, IBM and Toshiba entered into 2 years of joint research on TFT LCD manufacturing. The research would be conducted jointly by researchers at IBM's Yorktown Heights laboratories, IBM Japan, and Toshiba. Each company would host the project for 1 year in its respective facilities in Japan, starting at Toshiba, where a rudimentary R&D line was to be erected as soon as possible. At the end of the joint research project, each company would be free to pursue its own manufacturing plans or to walk away. On the strength of these discussions, Toshiba engineers apparently went immediately to work designing the line

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[8]My collaborators and I have written about these small manufacturers elsewhere (see, e.g., Lenway et al., 2000).

[9]For details, see Lenway et al. (2000) and Office of Technology Assessment of the U.S. Congress (1990).

and ordering equipment. The contract was officially signed and work began on August 1, 1986. One month later the R&D line was up and running.

By July 1988 both Sharp (Japan's pioneer and still-dominant TFT LCD manufacturer) and IBM-Toshiba had developed 14-inch TFT LCD prototypes, demonstrating a potential for flat video reproduction that had seemed remote only 5 years earlier. Sharp publicly announced its achievement, as is customary for Japanese companies. IBM-Toshiba did not at first announce their achievement, which was consistent with IBM company policy.[10] Toshiba later prevailed, and an announcement was made in the wake of the Sharp press conference. Both companies claimed the laurels for largest size and best resolution.

Nearly a year after the IBM-Toshiba prototype announcement, on August 30, 1989, the two companies announced their agreement to form a manufacturing alliance called Display Technologies, Inc. (DTI). The alliance was to be structured as a 50/50 joint venture between Toshiba and IBM Japan. The partners initially capitalized DTI at about $140 million (*Los Angeles Times*, 1989), of which $105 million was earmarked for a high-volume TFT LCD fabrication facility. DTI's headquarters and first fab would be located in Himeji City, next to one of Toshiba's STN LCD fabs. DTI officially started up on November 1, 1989. R&D for DTI was conducted in three laboratories, one in the United States and two in Japan: IBM's Thomas J. Watson Laboratory in Yorktown Heights, New York; IBM Japan's laboratory in Yamato; and Toshiba's laboratory in Himeji.

Thus, IBM was the only large U.S. firm to invest in high-volume TFT LCD manufacturing. It is important to note that IBM decided to do this in Japan with a large Japanese partner, Toshiba, partly because it believed this was the only way to become globally competitive. Japan was where the TFT LCD action was and where learning about the new industry could be maximized. The most important customer for IBM FPDs was the IBM PC Division in Florida, so locating production in Japan had little to do with servicing customers. IBM divested itself of its stake in DTI in 2001 when it no longer saw a need to have an internal supplier of TFT LCD panels. By then, there was plenty of competition in the global TFT LCD market and no difficulty finding the high-quality displays needed for IBM end products. IBM was not interested in LCD television sales (although perhaps it should have been). Like all the large Japanese electronics firms, except Sharp, IBM turned its attention to higher-value-added businesses, including very-high-definition FPDs, and to advanced services where potential profits and revenue growth were higher.[11]

[10]Out of sensitivity to U.S. antitrust law, IBM has remained reluctant since the 1950s to announce technology breakthroughs prior to the availability of products in markets.

[11]To date there has been no high-volume production of IBM's very-high-resolution displays. See IBM Research. Roentgen Project Page. Roentgen Introduction. http://www.research.ibm.com/roentgen/.

Corning

In fall 1986, a group of top executives in Corning held a meeting to decide on entering the market for LCD substrates. Corning research in New York and the marketing organization in Japan had followed FPD developments since the early 1980s through several major turning points. Around the time of Matsushita's 1986 pocket television introduction, a number of senior managers in Corning came to envision TFT glass substrates as a major business opportunity for Corning.

Corning gained experience selling glass in Japan for STN LCDs over many years, beginning in the early 1970s with sales to makers of watch and calculator displays. Corning researchers made an effort to develop extremely thin sheet glass for these applications, using a product the company was selling for use as microscope slide covers for medical laboratories. Corning had developed its proprietary fusion glassmaking technology as a method of fabricating extremely thin, optical-defect-free glass without the need for grinding or polishing.

Early LCD technologies, however, did not require the advanced properties of fusion glass. Most of Corning's sales for these applications continued to consist of glass manufactured using more conventional methods. But in the early 1980s, managers in Corning Japan noted with some surprise that the laboratories of several major electronics groups were placing regular, gradually increasing orders for a more advanced product, Corning's 7059 fusion-formed borosilicate glass.

Corning's proprietary fusion glass technology seemed uniquely matched to the apparent technological trajectory of TFT LCDs. Corning Japan's managers had worked diligently to nurture relationships with Japanese manufacturers. Even a technologically well-matched Japanese competitor would have faced difficulties building the same network and familiarity with market needs. For a competitor from outside Japan, these barriers would be insurmountable.

Corning's main research unit, located in Sullivan Park in Corning, New York, developed new products and manufacturing processes for LCD glass substrates. The first fusion glass machine was built there in the late 1970s. In 1982, Sullivan Park developed an ultrathin glass—Corning's 7059 fusion-formed borosilicate glass—that was used in TFT LCD laboratories around the world. Sullivan Park also developed the fusion glass process that was used in Harrodsburg in 1984. The collaboration between Sullivan Park and Harrodsburg continues to the present. The two locations recently co-developed a new glass called Eagle XG, which provides all the desirable properties required for TFT LCD substrates but does not contain arsenic, antimony, or barium. Eagle XG is therefore a greener product than its predecessor, Eagle^{2000}, which was introduced in 2000 and contained the three heavy metals. Corning tries out all new TFT LCD glass products and processes at Harrodsburg before transferring knowledge to its other facilities.

Corning opened a new glass melting and finishing facility for TFT substrates and a new TFT research center in Shizuoka Prefecture in 1989. Its growing TFT customer base in Japan would be served from both Shizuoka and Harrodsburg.

As the industry grew, Corning had to expand production rapidly. Demand for thinner substrates resulted in volume production of 0.7-mm glass in 1990 and 0.5-mm glass in 1998.

Samsung Corning Precision (a 50/50 joint venture established in 1995 between the two firms) began to produce substrates for Korean producers in Kumi in 1996. A major expansion in production capacity in all three locations—the United States, Japan, and Korea—occurred in 2000. A second Korean plant was opened in Cheonan in 2002 and reached volume production in 2003.[12]

In 2004, the firm began to produce TFT substrates in Tainan, Taiwan. It soon opened another plant in Taichung to service the rapidly growing demand for substrates in Taiwan. The governments of both Korea and Taiwan were concerned about the dependence of domestic TFT LCD manufacturers on foreign suppliers and the impact of that dependence on the balance of trade. Accordingly, they encouraged the establishment of domestic suppliers wherever possible but also urged foreign firms to establish local operations as soon as possible.

Corning broke ground for a substrate finishing plant in China in November 2006. Apparently the firm had started its manufacturing operations in Korea and Taiwan with finishing plants before establishing melting operations. Corning was waiting to see how rapidly the Chinese TFT LCD firms would be ramping up production before committing to a melting plant there.

Corning followed the shift in manufacturing of TFT LCDs as it moved successively from Japan to Korea to Taiwan. Corning had to move manufacturing and some research to East Asia, but most of the research on fusion glass remained in the United States (Guan, 2004). By 2004, roughly a third of Corning's total revenues ($3.8 billion) depended on the sales of TFT LCD substrates (*Newsday*, 2006). Corning's ability to remain a key participant in the TFT LCD industry depended on its proprietary fusion glass technology.

Applied Materials/AKT

Applied Materials, the U.S. semiconductor manufacturing equipment maker, started a display arm called Applied Display Technology in 1991. In 1993, Applied Materials initiated a strategic alliance with Komatsu, the Japanese heavy equipment maker, called Applied Komatsu Technology (AKT). AKT developed and manufactured TFT LCD manufacturing equipment in the United States using globally sourced components. The company maintained principal R&D and engineering facilities in Santa Clara, California; funded basic research in outside institutions such as universities; and also relied on the specialized R&D and basic research capabilities of its global supply network. In 1993, AKT established its

[12]Samsung Corning Precision Glass. "Company: General Information: History." http://www.scp.samsung.com.

headquarters in Kobe, Japan, and set up a technology center there but most R&D remained in California.[13]

The motivation for forming AKT did not revolve around the conventional joint venture criteria of market, technology, or capital seeking. The R&D was complete, the funds invested, and Applied Materials already enjoyed a prestigious position in Japan's semiconductor industry. Rather, Applied Materials actively sought an alliance partner to address the personnel requirements of sustaining and growing the new business. The industry would grow rapidly (no one at Applied Materials knew how quickly at the time). To keep pace, the new venture would need to expand rapidly in its abilities to conduct site installations and testing as well as continuing servicing of its machines at the customers' premises. Applied Materials offered to ally with Komatsu after a rigorous search for a partner that shared its beliefs about the necessary marriage of cost effectiveness, quality, and technological advancement. Komatsu invested $35 million initially in the new venture (*Electronic News*, 1993).

In October 1993, AKT announced that its commercial CVD tool, the AKT-1600, was ready for sale, for delivery 6-8 months after an order was placed. Beginning with the startup of the first Generation 2 manufacturing lines in mid-1994, all TFT LCD producers had the opportunity to benefit from the innovations incorporated in the new CVD tool. The AKT-1600 sold for about $5 million for a four-chamber production system, which could process about 40 substrates per hour. High-volume Generation 2 fabs needed about four of them.[14] By year's end, AKT had captured CVD market leadership by a wide margin.

Shortly thereafter, Hitachi approached AKT for a design to process a 400 × 500 substrate, out of which they could make four 11.3-inch displays. Hitachi ended up with a CVD tool that could process 370 × 470 substrates, a modification of the DTI design. By the end of the life cycle for Generation 2, AKT had modified the 1600 to accommodate 400 × 500 mm substrates for a Generation 2.5 line that Sharp started up in July 1995. Even the largest manufacturers remained indecisive regarding the best display size to manufacture and the best substrate size on which to manufacture it, but by supplying these firms with tools that matched their diverse specifications, AKT acquired knowledge that would allow it to be the dominant supplier of CVD equipment for years to come. Along with Corning, it would become a key participant in the global effort to establish an industry consensus on standards for next-generation equipment. Despite the movement of manufacturing from Japan to Korea and Taiwan, development of

[13]Applied Materials announced the joint venture's creation on June 17, 1993. According to Applied's 1999 Annual Report, the venture ended in 1998. AKT then reorganized as a wholly owned subsidiary of Applied Materials. Since the reorganization, Tetsuo Iwasaki has served as AKT's chairman, in addition to his position as chairman and CEO of Applied Materials Japan.

[14]Material for this paragraph was taken from *DisplaySearch Equipment and Materials Analysis and Forecast* (Austin, Tex.: DisplaySearch, 1999).

new equipment was accomplished primarily in Northern California even though machines had to be built and tested on factory floors in East Asia.

Photon Dynamics

Founded in 1986 by Francois Henley and headquartered in Milpitas, California, Photon Dynamics initially produced inspection and testing tools for semiconductor manufacturing and did not enter the FPD industry until 1991. The firm developed test, inspection, and repair systems for FPD manufacturing that were used to increase yield, reduce materials loss, get new designs from R&D into production, and assist in the rapid startup of new plants.

For TFT LCDs, materials costs (for glass substrates, color filters, and polarizers, for example) represent at least 40 percent of the cost of production. As a result, test and inspection of substrates is a key part of improving manufacturing efficiency. It is critical to identify defects and repair them as soon as possible prior to further processing to avoid wasting materials. When defects cannot be repaired, the substrate needs to be scrapped. The same goes for cells and assembled modules.

Photon Dynamics was able to sell to high-volume manufacturers in Japan, Korea, and Taiwan on the basis of being able to offer products and services competitive with those of its main competitors: Micronics Japan, AKT, and Shimadzu in array testing and NEC, NTN, and Hoya in cell and module testing. Two proprietary technologies played a key role in the early success of Photon Dynamics: voltage imaging and N-aliasing image processing.[15] The firm held over 20 patents in its intellectual property portfolio.

Unlike Corning and AKT, Photon Dynamics had no overseas research facilities. R&D was done mainly at its headquarters in San Jose, California. In 2005, the firm maintained sales and customer support offices in China (Beijing), Korea (Seoul, Daejeon, Kumi, and Cheonan), Taiwan (Hsinchu and Taichung), and Japan (Tokyo and Tsu). Some repair equipment was to be manufactured in Korea in 2007, but all other manufacturing was done in California.

Competition in Two TFT LCD Supplier Industries

Three U.S. suppliers were competitive in two industries that supplied important inputs to TFT LCD manufacturing: Corning in glass substrates, and AKT and Photon Dynamics in manufacturing and testing equipment. Corning's main

[15]Voltage imaging produces a two-dimensional image of the voltage distribution across the surface of a TFT array. It greatly reduces the amount of time needed to test an array prior to assembly into a TFT cell, which can greatly increase the yield and throughput of TFT LCD production facilities. N-aliasing image processing refers to special software algorithms used to detect defects or anomalies in the images produced by visual imaging equipment.

competitors were Asahi Glass and Nippon Electric Glass (NEG), both Japanese firms. Neither Asahi Glass nor NEG had developed fusion glass technology; therefore, they were at a disadvantage as the industry turned more and more to fusion glass as substrates grew larger. Corning's careful husbanding of its intellectual property rights in fusion glass technology was crucial to maintaining its competitive advantage.

AKT's main competitors in CVD equipment in 2005 were Unaxis-Balzers of Western Europe and Jusung of Taiwan. Photon Dynamics' main competitors were Micronics Japan, AKT, and Shimadzu in array testing and NEC, NTN, and Hoya in cell and module testing. Both were vigilant in protecting the intellectual property rights associated with their equipment and occasionally engaged in patent infringement suits to protect those rights.

All U.S. suppliers needed to locate warehouses and service facilities in Japan, Korea, and Taiwan close to major customers. As the industry matured, suppliers also felt pressure to locate manufacturing and R&D facilities in East Asia. These pressures arose because of governmental concerns about technological dependency and the impact of technological imports on the balance of trade. Asian governments wanted key technologies to be developed domestically. If domestic firms were unable to do this, then foreign firms would be encouraged to locate their development efforts in the country. Such pressures were generally resisted because the supplier firms wanted to maintain the core of scientific and engineering expertise closer to home. Corning experimented with a joint venture with Samsung that proved successful but the joint venture licensed fusion glass technology from Corning and was not permitted to compete with the parent firm in other markets. Corning located melting facilities in Japan, Korea, and Taiwan and was pressured to locate melting facilities in China, but so far had declined to do so.

PUBLIC POLICY ISSUES

In the background of this limited but important participation by U.S. firms in the TFT LCD industry is the slow and steady relative decline of innovative activity in LCDs in the United States (see Figure 6). At the very beginning of the FPD industry, RCA's Sarnoff Lab was a key location for cutting-edge research. The Sarnoff Lab developed the dynamic scattering mode display that was used in the first calculator with an LCD. Sarnoff licensed the patent to Sharp in 1973, the same year that it decided to end its LCD research program (Castellano, 2005; Johnstone, 1999). The Westinghouse laboratory's LCD R&D program, led by Peter Brody, was terminated in 1978 (Brody, 1996). Xerox's display efforts lasted considerably longer, culminating in the formation of a spinoff firm named dpiX in 1998, but dpiX never attempted to compete in high-volume display markets. Products based on its technology were too expensive for consumer markets.

When the U.S. government decided to consolidate a number of R&D programs relating to display technology in 1994, there was a flurry of research activity connected with the new emphasis on advanced displays, particularly on the part of the Defense Advanced Research Projects Agency (DARPA). Some important technological developments came out of these efforts. For example, the deformable mirrors that eventually became Texas Instruments' digital light processor technology now found in many projection televisions and data projectors were partially funded with the aid of DARPA grants and contracts (most of the funding came from Texas Instruments itself). DARPA provided some funding to firms like Photon Dynamics for TFT-LCD testing equipment. Firms like IBM, AKT, and Corning, in contrast, did not participate in these programs, except as observers, and did not receive major funding for further development of their core technologies.

A good example of decline in U.S. R&D capability in FPDs was the closing of a major government-funded display laboratory at the University of Michigan in the mid-1990s that had been started with DARPA funds but ended when the funding ran out.[16] The decline in capability was the result of lack of will on the part of the Republican-controlled Congress to fund FPD R&D efforts. Globalization played a key role in the evolution of the industry because the newer entrants in Korea and Taiwan were not able to match the technological resources that were available to Japanese firms and thus had to collaborate with firms in Japan, Western Europe, and the United States to solve some of the formidable problems of becoming globally competitive. This need to collaborate provided some U.S. supplier firms with opportunities to remain at the technological frontier even though no U.S.-owned firms were manufacturing TFT LCDs after the year 2001. However, since much of the innovation in the industry was connected with designing new commercial products and new manufacturing processes, U.S. firms who were not major suppliers to the industry and most U.S. laboratories and universities were increasingly unable to participate meaningfully in the industry.

CONCLUSIONS

In general, innovative activity has tended to follow investment in manufacturing in the FPD industry, but some important innovation continues to occur that is not necessarily located close to manufacturing. Scientists and engineers in East Asia have an important advantage over U.S. scientists and engineers because of the location of manufacturing there; nevertheless, some U.S. firms have remained key participants in the industry and their scientists and engineers have been able to contribute in very important ways to innovation in the industry. Without firms like IBM, Corning, Applied Materials, and Photon Dynamics, the FPD industry would not have been able to solve important scientific and technological problems. While the main benefit to date from innovative activity in this industry

[16] For further details, see Murtha et al. (2001, ch. 6).

has probably been captured mainly by firms and workers in Japan, Korea, and Taiwan, a not insubstantial number of beneficiaries can be found in the United States as well. The nearly 400 workers employed by Corning in its fusion glass facility in Harrodsburg, Kentucky, are an example.

A key lesson to be drawn is that U.S. supplier firms that are willing to establish service centers abroad and to work collaboratively with foreign firms wherever the latter are located can remain internationally competitive even in industries where manufacturing is primarily located abroad. Such willingness to collaborate does not necessarily imply the offshoring of formerly U.S.-based R&D, as the cases of Corning, AKT, and Photon Dynamics illustrate. On the contrary, the willingness to collaborate ensures that some important innovative activity will continue to occur in the United States. Any government policies that prevent firms from doing this are likely to be highly counterproductive. U.S. firms have many strengths that derive from the emphasis on government sponsorship of basic research, relatively strict enforcement of competition and intellectual property laws, the availability of venture capital for startups, and a generally favorable climate for entrepreneurship. If the United States wants to participate in dynamic, globalized industries like the FPD industry, it has to keep its economic nationalists on a short leash.

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