The Domestic Flat Panel Display Industry: Cause for Concern? 2

The lack of a strong domestic flat panel display (FPD) industry has led to two areas of concern for the nation: loss of economic benefits and threats to national security. This chapter examines the benefits that could accrue to the nation if a domestic high-volume FPD industry were developed. The economic benefits (or potential losses if such an industry is not developed) could come in three forms:

1. *Profits that could accrue to manufacturers*. Manufacturing displays for a large and rapidly growing market could be the source of profits and jobs for American companies and workers.
2. *Benefits to FPD users from having access to a domestic industry.* Diversification of FPDs and increasing integration of functions onto the display have the potential to put domestic FPD users at a disadvantage; developing a domestic capability could ameliorate such problems.
3. *Spillovers to related industries*. There are some spillovers between FPD and semiconductor manufacturing processes; a high-volume domestic FPD industry could help the materials and equipment infrastructure of the semiconductor industry.

The profits that might accrue to domestic producers are dependent on the structure of the world FPD industry and markets, future growth patterns, technology developments, and product uses. The potential benefits to downstream industries that use FPDs are dependent on the structure of worldwide supply and the development of display technology. Possible spillovers to related industries will be driven by developments in manufacturing technology and markets. All of these issues are investigated in the first three parts of this chapter.

The second set of potential benefits from developing a high-volume domestic FPD industry applies to national security. FPD technologies will increasingly be used in the design, manufacturing, and retrofit of military systems. The Department of Defense (DOD) is concerned that it does not have early, assured, and affordable access to leading-edge FPD technology for these systems. There are three reasons for this concern:

1. Military demand is and will remain a small fraction of the world FPD market, thus limiting the effectiveness of DOD procurement in shaping the domestic industry;
2. Military display requirements are widely varying and often differ from commercial requirements in their final form; and
3. The concentration of FPD manufacturing capacity in Japan to date has raised concerns over U.S. military access to FPD technologies.

DOD has determined that the best way to meet its goal of early, assured, and affordable access to FPDs is through a dual-use strategy that relies on the development of a domestic high-volume FPD industry. In order to examine the benefits that would accrue to the military from the development of such an industry, it is instructive to examine the current status of the development and procurement process for military FPDs.

As the final section in this chapter illustrates, many military display requirements are currently filled through a combination of foreign-produced commercial displays and domestically produced custom displays. While foreign suppliers may not guarantee the timeliness and assured access that DOD desires, defense contractors that modify foreign-produced commercial displays deliver systems that perform adequately for many missions at a competitive price. Regardless of whether a display is produced domestically or abroad, and for both custom- and commercially manufactured displays, the cost of adapting displays for military systems is much higher than the cost of the display itself.

DEMAND FOR FLAT PANEL DISPLAYS

The demand for FPDs is large and increasing by more than 10 percent annually (measured by value). There are numerous technologies available for creating an FPD. The demand is greatest for liquid crystal displays (LCDs), and, increasingly, for active matrix LCDs (AMLCDs) used in portable computing devices. The FPD market will exceed $10 billion in 1995, and is expected to range from $20 billion to $40 billion by the turn of the century. One source of uncertainty in the estimates is the relationship between growing demand and falling prices: it is not clear how rapidly manufacturing costs (and thus prices) for FPDs will fall, which makes the increase in demand difficult to predict. While critical to the U.S. military, FPDs for military systems represent less than one percent of worldwide demand, and are not likely to grow as a share of the overall market.

Flat Panel Display Technologies and Markets

FPDs are electronic displays that present images in a thin package (see box 2-1). FPDs have been used in two ways. First, they have been widely adopted as replacements for mechanical or other types of electrical displays for indicators, gauges, and dials in numerous systems, such as watches, calculators, gas pumps, and test equipment. Second, more complex FPDs have enabled the development of laptop computers, notebook computers, personal digital assistants, and other handheld and portable computers. In the future, FPDs may begin to replace bulky cathode ray tubes (CRTs) in desktop computer monitors and home televisions, and may allow large-screen televisions thin enough to hang on a wall.

The world FPD industry has grown steadily since the early 1980s (see figure 2-1). Growth was fueled in the mid-1980s by the introduction of FPD-based pocket televisions, and in the early 1990s by the use of FPDs in the rapidly growing laptop computer market. Throughout the 1990s,

BOX 2-1: Display Technologies

Flat panel display (FPD) is a term used to describe technology that presents visual information in a package with a depth much smaller than its horizontal or vertical dimensions. FPDs can be used in many applications that the cathode ray tube (CRT), the mainstay of video displays for five decades and used in most home televisions and desktop computer displays, cannot The CRT is generally as deep as the width of the screen; because the entire CRT IS glass, the package IS both heavy and large

In general, FPDs are constructed by sandwiching a material that IS electro-optically active (one that—in response to an applied electric field-either modifies the transmission or reflection of an external light source, or emits light) between glass plates. Transparent horizontal and vertical electrical conductors are deposited on the plates, forming rows and columns in a grid pattern. Individual picture elements, or *pixels,* are defined by each intersection of a row and a column. The modulation or emission of light by each pixel is controlled through the application of voltage to the electrodes. In some displays (including passive matrix liquid crystal displays), the voltage difference between a pixel's row-and-column electrodes directly acts on the material between the glass plates; in other displays (including active matrix liquid crystal displays), the voltages on a pixel's row-and-column electrodes are used to set an electronic element such as a transistor, which in turn acts on the material between the glass plates. The latter approach gives better performance, but the added electronic elements make manufacturing more difficult.

Figures and text can be represented on FPDs by the application of electrical signals to the display matrix. The FPDs that account for the largest market share (measured by value), demonstrate the fastest predicted growth, and use the most challenging manufacturing process are high-information-content displays. [1] These displays are demanded by most computer, business, communications, and transportation applications, and a large fraction of consumer and industrial applications (see appendix A for a more detailed discussion of FPDs).

There are four types of commercially available high-information-content FPDs:

1. *Passive matrix liquid crystal displays (PMLCDs)* are one of the main types of transmissive displays. They use liquid crystal materials, controlled by electrical signals on a grid, to affect the transmission of light.
2. *Active matrix liquid crystal displays (AMLCDs)* are another type of transmissive display. The AM LCD builds on the PM LCD by using switching elements located at each pixel to control display performance.
3. *Electroluminescent displays (ELs)* are one type of emissive display currently available. EL FPDs use a solid phosphor material that glows when exposed to an electric field.
4. *Plasma displays,* another type of emissive display, use a gas to create a single color directly or to create multiple colors indirectly by energizing colored phosphors.

Other FPD technologies are being or have been evaluated and developed for high-information-content applications; the two most promlsing are: 1) the field emission display (FED), a type of emissive FPD that IS a flat version of a CRT; and 2) the digital micromirror device (DMD), a reflective FPD that is an array of miniature mirrors whose positions can be electrically controlled to reflect light, forming an image on a screen. The four most common high-information-content FPD technologies can be compared with the CRT in terms of several performance criteria (see table below).

(continued)

[1] The U S Department of Commerce has defined any display with more than 120,000 pixels—corresponding to a full-page display, consisting of 25 rows by 80 columns, with 5 by 7 dot matrix characters—as high information content A more typical format IS VGA (video graphics adapter), comprised of 480 by 640 pixels, in a color display, there are three copies of each pixel, for nearly one million pixels

BOX 2-1: Display Technologies (Cont'd.)

Flat Panel Display Technologies Performance Comparison

Feature	Passive matrix LCD	Active matrix LCD	Electro-luminescent	Plasma	Cathode ray tube
Resolution	medium	high	medium/high	medium/high	high
Luminance	medium	high	medium	medium	high
Contrast	medium	high	medium/high	low/medium	medium
Ambient contrast	medium	high	low/high	medium	low
Gray scale	low	high	medium	medium	high
Number of colors	medium	high	medium/high	medium/high	high
Viewing angle	low	medium	high	high	high
Screen update time	slow	fast	fast	fast	fast
Temperature range	narrow	narrow	wide	medium/wide	wide
Vibration capacity	high	high	medium	medium	low
Power	low	low	medium	medium	high
Volume	low	low	low	low	high
Weight	low	low	low	medium	high

KEY LCD = Iiquid crystal display

NOTE Shaded boxes indicate display technology weaknesses,

SOURCE Louis D. Silverstein, "Color in CRT and LC Displays, " *1994 SID International Symposium Seminar Lecture Notes* (Santa Ana, CA Society for Information Display, 1994), vol 2, p F-3/5.

- *Resolution* is a measure of the smallest detail that can be displayed, for computing tasks that use graphic Interfaces (such as Windows), high resolution is required,
- *Luminance* is a measure of brightness, *contrast* is a measure of the ratio of a light pixel to a dark pixel, and *ambient contrast* is a measure of contrast in the presence of ambient light Many applications, like portable devices, demand high luminance, contrast, and ambient contrast.
- Gray scale is the number of discrete levels (shades) to which a pixel can be set; this affects the degree of shading possible in a monochrome (black and white) display, and is a factor in the number of colors achievable by a color display.
- *Viewing angle* is the angular measure of the decrease in contrast that results in viewing the display from a position other than head-on, a low viewing angle means that the user must be directly in front of a screen in order to perceive a comfortable level of contrast
- Fast *screen update time* IS required for the display of full-motion video, as from a television signal, and for the display of some computer tasks, such as rapid cursor movement,
- *Temperature range* *IS* the breadth of ambient temperatures in which the display can effectively operate, some displays are adversely affected by exposure to temperatures outside of a set narrow range,
- Vibration capacity refers to the ability of a display to withstand external shocks without adverse effects on performance.
- Finally, *low power consumption, volume,* and *weight* are key attributes of portable displays

AMLCDs match or exceed the performance of CRTs in all categories except for viewing angle and temperature range. The AMLCD is the fastest growing type of display technology, and it is likely to surpass the PMLCD as the largest FPD market segment, in terms of value, in 1996. The reason that AMLCD technology has become the leading approach to FPD manufacturing is that the combination of high performance, low weight, and small volume it offers makes it well suited for use in portable computing devices, a fast-growing market, The main Iimitation to adopting AMLCD technology in other systems—such as home televisions and desktop computers—has been the high manufacturing costs relative to the

(continued)

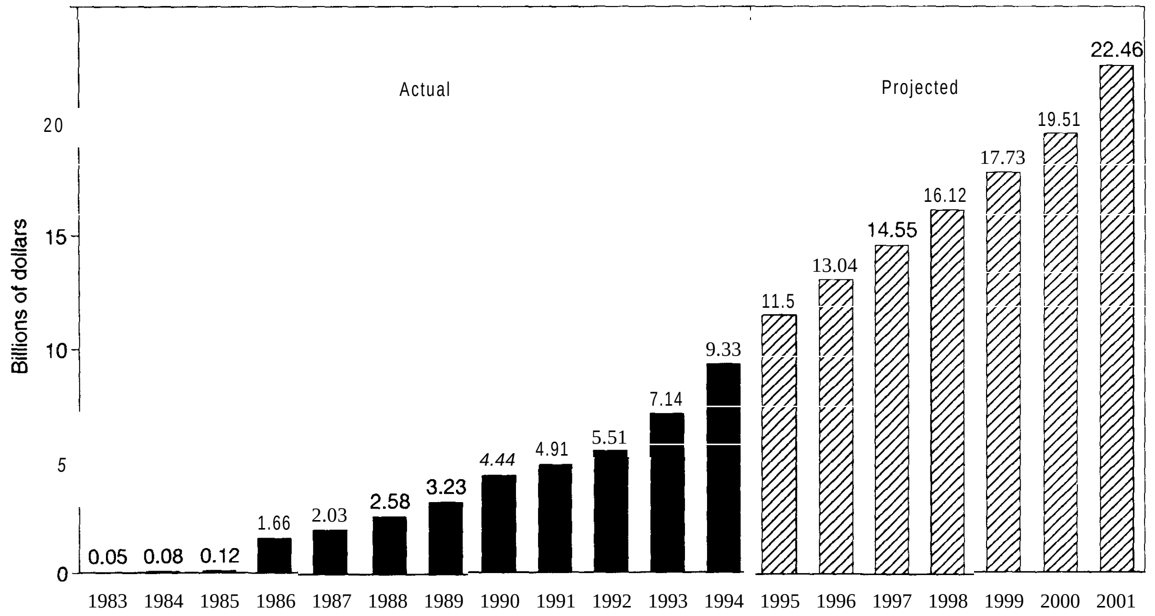
BOX 2-1: Display Technologies

CRT, a mature and relatively inexpensive technology. EL and plasma displays match or exceed the performance of AMLCDs in some measures, and are used for military, industrial, medical, and other applications that demand high performance in viewing angle or temperature range. While offering the lowest overall performance, PMLCDs are a mature technology and are inexpensive to manufacture PMLCDs offer adequate performance for applications such as simple text/numeric displays in equipment, appliances, and timepieces, and have also remained a low-cost alternative to AMLCD in less demanding portable computer applications.

The growing dominance of the AMLCD could be challenged by one of several FPD technologies in development. in particular, FEDs are anticipated to match or exceed the performance of AMLCDs, and may also have significantly lower manufacturing costs.

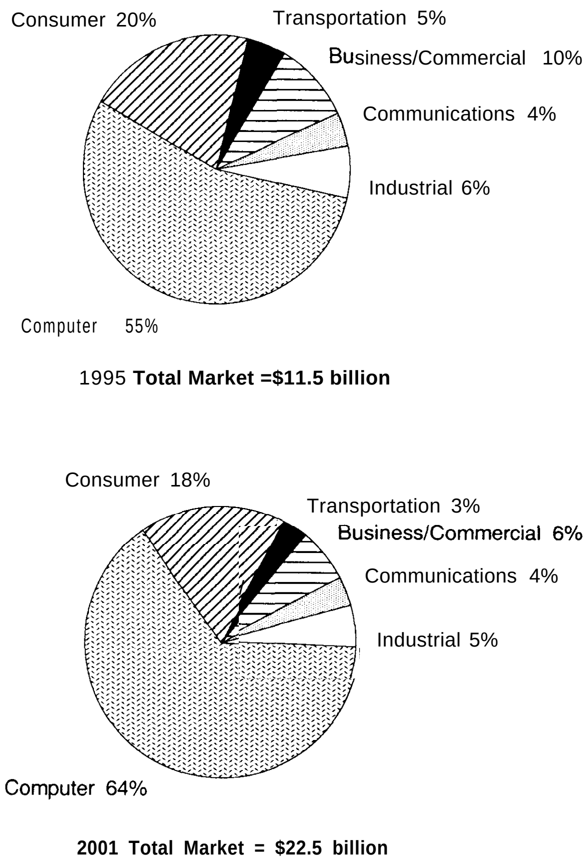
SOURCE Office of Technology Assessment, 1995

FIGURE 2-1: Worldwide Flat Panel Display Market, All Sizes, Types, and Applications: 1983-2001



SOURCE David Mentley, Director, Display Industry Research, Stanford Resources, Inc. , San Jose, CA, personal communication, Mar 21, 1995

FIGURE 2-2: Projected Worldwide Flat Panel Display Market Shares by Application 1995 and 2001



SOURCE: David Mentley, Director, Display Industry Research, Stanford Resources, Inc. , personal communication, Mar 21, 1995

rapid growth in the market for portable computers has driven the demand for FPDs and provided a large application base for which standard types of FPDs have been developed. in this large portion of the market, manufacturing-based competition has emerged; profits are dictated by manufacturing costs rather than product design.

The projections in figure 2-1 represent an average annual growth rate of 12 percent between 1995, when the market is projected to be $11.5 billion, and the year 2001, when it is projected to be $22.5 billion. Other sources have used higher rates of growth in their projections. One source is the Japanese electronics magazine, *Nikkei Microdevices*, which calculated that the growth rate of LCD production from 1990 to 1995 has averaged 32 percent per year, with a predicted 1995 production value of 1.25 trillion yen (approximately $15 billion at current exchange rates).[1] Projecting a continuation of this growth rate, the magazine has estimated that LCD production will exceed 4 trillion yen (approximately $47 billion using current rates) by the turn of the century. The disparity in these estimates reflects the uncertainties in this growing industry. The more conservative estimate in figure 2-1 is based on projected growth rates in current applications; it does not include potential new FPD applications. The Japanese estimates are based on production plans; they do not take into account whether or not the displays will actually be purchased (seethe following section on display supply).

The FPD technology projected to lead the market in growth is the active matrix liquid crystal display (AMLCD, see box 2-l), which is used in computers, the fastest growing application. Most computer applications are portable devices: laptops, notebooks, and handheld or pen-based computers that require light, compact, and low-power-consumption displays. Computers have been the largest FPD application for the past several years and demand is projected to grow faster—at an average annual growth rate of approximately 16 percent—than any other segment between 1995 and 2001 (see figure 2-2). Firms have manufactured notebook screens that are increasingly larger in diameter and higher in

[1] "Scale of Liquid Crystal Industry Assessed," in *Flat Panel Display 1995, Nikkei Microdevices,* Dec. 9, 1994, pp. 74-80 (translation provided by Maurice Cloutier, Foreign Broadcast Information Service). The estimates were taken from a poll of Japanese and Korean LCD producers; the years are Japanese fiscal years, which begin on April 1. in an article in the same publication, Samsung predicted a $28-billion LCD market by the year 2000.

resolution, and desktop PC and workstation FPDs are now appearing in the market.

Other applications include consumer items, industrial equipment, communication systems, business systems, and transportation systems. The consumer items that use FPDs include portable televisions, video games, camcorders, personal organizers, and memo devices; future applications may include high definition televisions. Industrial equipment includes test and analytical equipment, medical instrumentation, and factory/inventory control devices. Communications applications include portable phones, video phones, and pagers. Business systems incorporating displays include office equipment, overhead projectors, financial terminals, and large-screen public displays. Displays in transportation systems include instrumentation in pleasure boats, aircraft cockpits, and automobiles, as well as passenger entertainment systems in aircraft, trains, and, potentially, automobiles.

High-information-content displays (see box 2-1) account for more than 90 percent of the display market, measured by value. These FPDs are currently based on several technologies, and many more technologies are in the research and development stage. The leading technologies are the passive matrix liquid crystal display (PMLCD) and the AMLCD, each accounting for 43 percent of the market in 1995 (see figure 2-3). AMLCD technology is projected to grow at 16 percent annually between 1995 and 2001, far outpacing all other technologies. The growth of AMLCDs may be limited by new color PMLCDs using *dual-scan* technology, which approaches AMLCD performance at lower prices.

Much smaller shares are held by plasma displays (3 percent) and electroluminescent (EL) displays (1 percent), neither of which is expected to grow as a share of the market before 2001. Technologies that are only used for low-information-content applications, such as alphanumeric indicators on appliances, make up another 10 percent of the FPD market. The leading technologies in this market segment are light emitting diodes (LEDs) and vacuum fluorescent displays (VFDs), which to date have not been suitable for high-information-content displays. There is also a possibility that technologies not yet in production, such as field emission displays (FEDs) and digital micromirror devices, may capture significant market share in coming years.

The Military Market

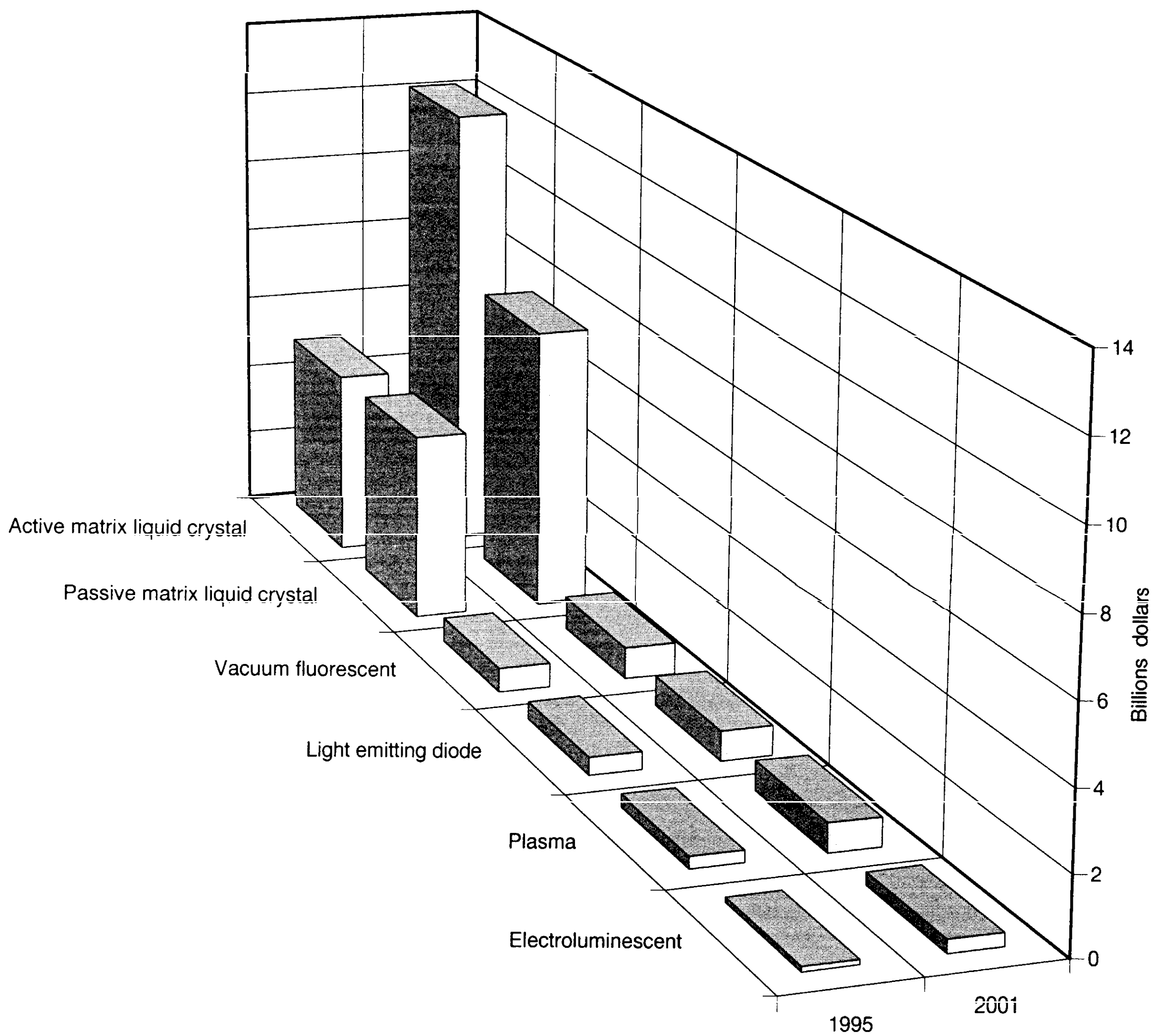
Current military applications include command and control systems, aircraft cockpits, ground vehicles, air traffic control, and portable and head mounted infantry systems. However, the military portion of the FPD market is quite small, and is not expected to exceed a few percent of the total world market in the foreseeable future (see figure 2-4). DOD's estimate of the military demand for FPDs over the next 25 years shows modest growth until 2009; projected annual demands range from 15,000 to 25,000 displays (see figure 2-5), compared to an overall market demand in the tens of millions. After 2010, when head mounted systems are expected to become standard equipment for soldiers, the annual requirements will increase sharply, but are not expected to exceed 100,000. The largest component of future military demand—displays from 0.5 to 5 inches in diameter used in projection and head mounted systems—is currently a small part of the commercial market, but may be used in the future for commercial projection displays and virtual reality systems.

SUPPLY OF FLAT PANEL DISPLAYS

The FPD industry is diversified in terms of applications markets and technology types, but there is an increasing trend toward the use of LCDs, and particularly AMLCDs, in portable computer and communications devices. During the early 1990s, a few Japanese companies such as Sharp, Toshiba, and NEC dominated FPD production through large investments in LCD manufacturing.

More recently, however, large investments in LCD production have been made by many other Japanese companies, as well as a few Korean, Taiwanese, and European companies, thus decreasing the industry concentration. Although FPD demand growth rates are projected to be high, in-

FIGURE 2-3: Projected Worldwide Flat Panel Display Market by Technology, 1995 and 2001

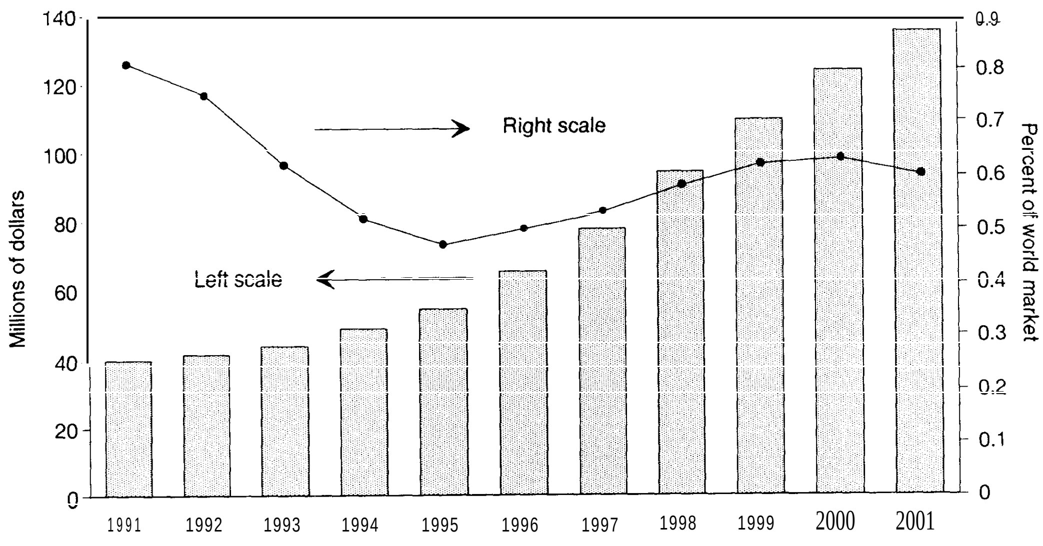


SOURCE: David Mentley, Director, Display Industry Research, Stanford Resources, Inc., personal communication, Mar. 21, 1995.

vestments announced worldwide in FPD manufacturing facilities will likely result in manufacturing capacity that will exceed demand. This will result in downward pressure on FPD prices (which could stimulate additional demand), and could also result in reduced profits for FPD manufacturers. A recent report states that profit margins have deteriorated since the end of 1994 for leading AMLCD producers. The report asserts that a *typical firm* that began production in 1992 did not reach profitability until 1994; is likely to show zero profits throughout the second half of 1995; and will return small profits in 1996 and 1997.[2]

[2]Hideki Wakabayashi, "Is Confidence in the Growth Potential of the LCD Panel Market About To Collapse?" Nomura Research Institute, Tokyo, May 25, 1995.

FIGURE 2-4: Military Flat Panel Display Sales: Total Sales and Percent of the World Market, 1991-2001



NOTE Values for 1995-2001 are projections

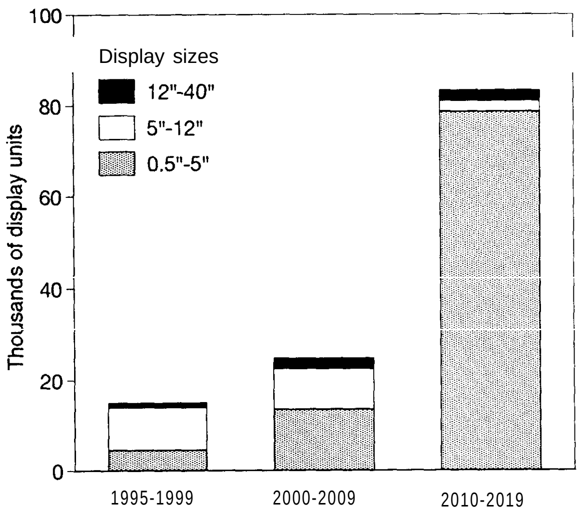
SOURCES Military market figures from Len Zuga, *U S Military Display Markets :New Technologies, Upgrades, and Government Funding Brighter? Market,* Report 5207-16 (Mountain View, CA Frost& Sullivan, 1995), figures 3-1 and 3-2, size of world market from figure 2-1 above

The large investments made by East Asian firms have created barriers to production for potential U.S. entrants, and the recent growth of investment in AMLCDs has made entry in that technology even less attractive. Taken as a whole, the small investment made by U.S. firms has been spread among several FPD technologies, and has not been sufficient to develop high-volume production capabilities.

▮ FPD Production in Japan

Most current FPD production is in LCDs produced in Japan. During Japanese fiscal year 1994, LCD manufacturers planned to produce more than $8 billion in displays (see table 2-l). Japanese manufacturers have made large investments in LCD manufacturing plant and equipment since the late 1980s. Definitive measures of investments are difficult to obtain because of difficulties in verifying whether announcements have been followed through, uncertainties in determining exactly what the investments were for (i.e., physi-

FIGURE 2-5: Estimated Annual Defense Demand for FPDs, by Units and Size, 1995-2019



SOURCE :U.S. Department of Defense, *Building U.S. Capabilities in Flat Panel Displays: Report of the Flat Panel Display Task Force,* October 1994, figure 3-8

TABLE 2-1: Announced Investment and Production by Japanese LCD Producers (in hundreds of millions of yen[a])

Company	FY 1989-93[b] investment (reported)	FY 1994-95[b] investment (planned)	FY 1994[b] production value (forecast)
Sharp	1,600	870	2,300
Toshiba[c]	820	850	1,100
NEC	430	500	800
Seiko-Epson	535	180	700
Sanyo Electric[d]	270	300	630
Hitachi	250	200	550
Casio Computer	835	100	450
Optrex	170	100	430
Hosiden	380	190	350
Matsushita Electric	640	200	350
Kyocera	105	150	130
Mitsubishi Electric[e]	525	430	40
Fujitsu	290	230	20
Others[f]	640	200	400
Total	7,490	4,500	8,250

KEY: LCD = liquid crystal display

NOTES:

[a]The values are reported in yen, because the Investments are given for multiple years in some cases, and there have been large fluctuations in yen/dollar exchange rates during that period, no conversion is made At the 1994 exchange rate of 100 yen/dollar, the figures translate to millions of dollars

[b]The Japanese fiscal year begins on April 1; FY 1994 ended March 31, 1995

[c]Figures for Toshiba include its investment in and production share from Display Technology, inc., a joint venture with IBM Japan.

[d]Figures for Sanyo Electric include Tottori Sanyo.

[e]Figures for Mitsubishi Electric are mainly comprised of Advanced Display Inc. , a joint venture with Asahi Glass.

[f]Alps Electric, Canon, Citizen Watch, Ricoh, Rohm, Seiko-Denshi Koygo, Sony, and Stanley Electric.

SOURCES. "Scale of Liquid Crystal Industry Assessed," in *Flat Panel Display 1995, Nikkei Microdevices,* Dec. 9, 1994, pp. 74-80, chart 2 (translation provided by Maurice Cloutier, Foreign Broadcast Information Service), updates from H Wakabayashi, "IS Confidence in the Growth Potential of the LCD Panel Market About to Collapse?" Nomura Research Institute, May 25, 1995

cal plant, capital equipment, or materials), and other uncertainties. However, announced capital expenditures are a reasonable guide to the order of magnitude of Japanese FPD investments.

Total investments made through 1993 resulted in roughly equal amounts of LCD output in 1994. The leading firms had lower ratios of investment to production than other firms; this is likely due to the weighting of investments by the leaders toward the beginning of the measurement period, which has resulted in increased production capacity. If one equates the value of production with revenues, these estimates bear out an investment to revenue ratio of l-to-l made by one industry analyst.[3]

The top three producers of LCDs (and, more broadly, of FPDs) in 1995 are Sharp, Toshiba, and NEC. Sharp is the leading producer of both PMLCDs and AMLCDs (and is also a leading producer of EL FPDs). Sharp's dominance in

[3]See David Mentley, "Forecast Inflation," */international Display Report,* Stanford Resources, Inc., San Jose, CA (distributed electronically by SEMI Newsletter Service), Nov. 15, 1994. Announced production does not equal revenues, since some production may have gone unsold and some sales may be from preexisting inventory. These figures are for LCD plants only, and do not include investments in other FPD technologies such as plasma; for example, Fujitsu, NHK, and Matsushita are leading plasma manufacturers. Fujitsu recently announced that it will invest $941 million in a plant to produce plasma screens measuring one meter in diagonal; see "Fujitsu Betting On Plasma Display s," *Electronic Engineering Times,* June 5, 1995, p. 28.

TABLE 2-2: Evolution in Japanese Active Matrix Liquid Crystal Display Production

Generation	Zero[a]	First	Second	Third	Fourth
Year begun	1987	1990	1993	1995	around 1997
Size of glass substrate	150x1 50 mm 150x200 mm	300x350 mm 300x400 mm 320x400 mm	370x470 mm 380x480 mm 400x500 mm	550x650 mm 500x600 mm 500x700 mm	560x720 mm
Displays per substrate (number and size)	1 (6-inch) or 1 (9-inch)	4 (6-inch), 4 (8-inch), or 2 (l O-inch)	6 (7-inch), 4 (l O-inch), or 2 (14-inch)	6(1 O-inch), 4 (14-inch), or 1 (30-inch)	9(10-inch), 4 (1 6-inch), or 2 (21 -inch)
New applications	Portable TV	Laptop PC	Portable and desktop PCs	Engineering workstation	

NOTE.
[a]The first active matrix liquid crystal display fabrication lines used converted semiconductor equipment, dedicated lines were not built until the late 1980s

SOURCES: Tannas Electronics, cited in Pete Singer, "Flat Panel Displays: An Interesting Test Case for the U.S. ," *Semiconductor International,* July 1994, P 78; Lawrence E Tannas and Robert A Burmeister, "Electronic Display Forum& EDEX'95 at SEMICON/FPD Yokohama, "ATIP95 20, Asian Technology Information Program, May 13, 1995

LCD production has led to concerns about the potential for monopolistic behavior. However, due to the continuing investments made by more than 15 other Japanese firms (see table 2-1) and other companies, Sharp's share of Japanese LCD production has fallen. in 1993, Sharp's share of Japanese AMLCD production value was 42 percent, but fell to 36 percent in 1994; in PMLCDs, its share fell from 24 percent to 20 percent.[4] Toshiba (including its share of Display Technology Inc., a joint production venture with IBM) is the third-largest producer of both AMLCDs and PMLCDs; most of its AMLCD production is used internally, but it sells PMLCDs and some AMLCDs on the merchant market. NEC is the second-largest AMLCD producer (it does not make PMLCDs); it has been increasing the share of its production sold on the merchant market, from 30 percent in 1994 to 50 percent by the end of 1995.[5]

AMLCD manufacturing has been through several stages or generations (see table 2-2). The early investments were devoted to funding the first two generations of AMLCD manufacturing technology; present and planned investments are financing the third and fourth generations. As manufacturing processes have become more complex, the required investment has increased. However, capacity has increased in each generation, and as each firm increased its manufacturing experience, the yield (percentage of working displays) steadily improved. These two factors have brought down manufacturing costs. Existing LCD production lines are comprised of three generations; Sharp is the leading adopter of new production technology (see table 2-3). Actual output of working displays from existing plants varies with the number of displays per substrate and the yield rate.

Several government-supported consortia in Japan have conducted R&D on display technologies, and government corporations have also been involved. The leading government agencies for display research have been the Ministry of Trade and Industry (MITI) and the Ministry of Posts and Telecommunications (MPT). The primary government consortia and corporations are:

[4]Market shares calculated from "scale of Liquid Crystal Industry Assessed," op. cit., footnote 1, chart 2 for firms' production estimates and figure 1 for estimates of total production. Years cited are Japanese fiscal years, which begin on April 1.

[5]Charles L. Cohen, "Japan Puts More into LCD plants," *Electronic Buyers' News,* June 5, 1995, p. 1.

TABLE 2-3: Liquid Crystal Display Production Lines in Japan

Company	Generation	Plant	cost (¥100M[a])	Substrate size (mm)	Date online	Initial capacity (substrates/ month)[b]	Full capacity (substrates/ month)[b]
Sharp	1	Tenri NF1	270	320 X 400	Fall 1991	n/a	30,000
	2	Tenri NF2	250	360 X 465	May 1994	n/a	15,000[c]
	2	Tenri NF3	250	370 x 470	June 1994	n/a	15,000[c]
	3	Mie 1	530	n/a	July 1995	n/a	5,000[c]
	n/a	Mie 2	n/a	550 X 650	July 1995	10,000[c]	n/a
DTI	1	Himeji	280	300 x 400	Oct. 1991	n/a	30,000
	2	Himeji	320	360 X 465	June 1994	n/a	30,000
	3	IBM Yasu	400	550 X 650	4th qtr. 1995	10,000	65,000[c]
NEC	1	Kagoshima 1	200	300 x 350	Aug. 1990	n/a	22,000
	2	Kagoshima 2	330	360 X 465	Dec. 1993	15,000	30,000
	n/a	Akita	300	370 x 470	Late 1995	15,000	30,000
Hosiden	1	Kobe	180	270 X 320	Aug. 1993	n/a	60,000
	2	Kobe	200	400 x 500	Late 1995	10,000	25,000[c]
Hitachi	1	Mobara	100	200 X 270	Late 1989	n/a	10,000
	2	Mobara	300	370 x 470	Late 1994	n/a	30,000
Casio	2	Kochi (2)	285	370 x 470	May 1994	n/a	12,000
Fujitsu	1	Yonago	205	300 x 400	Mar. 1994	n/a	8,000
	2	Yonago	180	370 x 470	1996	n/a	26,000
Mitsubishi	1	Kumamoto(1)	280	300 x 400	Feb. 1993	n/a	15,000
ADI	2	Kumamoto(2)	130	370 x 470	June 1995	10,000	25,000

NOTES.
[a]The values are reported in yen; because the Investments are given for multiple years in some cases, and there have been large fluctuations in yen/ dollar exchange rates during that period, no conversion is made. At the 1994 exchange rate of 100 yen/dollar, the figures translate to millions of dollars
[b]The actual number of displays varies: see table 2-2 for potential displays for each substrate size.
[c]Estimate made by *Nikkei Microdevices*

SOURCE: "Scale of Liquid Crystal Industry Assessed," in *Flat Panel Display 1995, Nikkei Microdevices, Dec. 9, 1994,* pp. 74-80, chart 3 (translation provided by Maurice Cloutier, Foreign Broadcast Information Service).

- *Giant Technology Corp. (GTC),* a consortium organized by the Japan Key Technology Center (JKTC, a joint partnership between MITI and MPT) in 1989 to develop meter-sized AMLCD panels for high resolution displays and other applications, including printing, copying, and solar cells. This ambitious goal has since been scaled back and GTC has begun to emphasize AMLCD process technology and color plasma display research. GTC has a budget of approximately $25 million, 70 percent of which comes from JKTC and the remainder from the 17 member companies, including Thomson and Hoescht.
- *High Definition Television Engineering Corp. (HDTEC),* also a JKTC-funded consortium. The program seeks to develop an LCD projector for high definition television (HDTV) applications. There are several companies participating in the $30-million program, again with 70-percent funding from JKTC. The primary participants are NHK, Seiko-Epson, and NEC.
- *The Japan Broadcasting Co. (NHK),* Japan's public broadcasting corporation, has been conducting research in HDTV for the past few decades. Its Science and Technical Laboratories have a $60-million budget that funds nine research divisions, several of which involve display technologies. NHK has concentrated on large color plasma panels for HDTV monitors. It has a division dedicated to transferring

technology to the private sector, and carries out joint development projects with industry.

- *Nippon Telephone and Telegraph (NTT)*, which does not manufacture equipment, but conducts research and transfers it to the private sector. Traditionally the government telephone corporation, NTT is now partially privatized.

FPD Production in East Asia and Europe

In addition to Japanese FPD investments, firms in East Asia—led by Samsung of Korea—and in Europe—led by the consortium known as the Flat Panel Display Co.—are also adding to the global FPD production capacity.

Korea and Taiwan

Throughout East Asia (outside of Japan), there are efforts to enter into the FPD industry; there is even assembly of simple LCDs in the People's Republic of China. In 1994, 7 percent of PMLCDs and 1 percent of AMLCDs were manufactured by East Asian firms based outside of Japan.[6] Especially in PMLCDs, manufacturing has matured to the extent that Japanese firms have moved production—28 percent in 1992—to foreign sites owned by Japanese firms.[7]

Japanese firms do not yet produce AMLCDs outside of Japan. However, firms in the Republic of Korea (South Korea)—Samsung in particular—are leading the race to develop AMLCD production capabilities, followed by companies in the Republic of China (Taiwan). Korean and Taiwanese firms have entered the FPD industry for different reasons.[8] In general, Korean firms appear to view FPDs as an important industry on its own as a potential successor industry to CRTs. CRTs are a $2-billion industry in Korea, but Samsung estimates that the value of LCD production will overtake that of CRTs in 1998.[9] FPDs are also viewed as a companion industry to semiconductors, one that could take advantage of the existing manufacturing infrastructure. It is also hoped that a strong FPD industry will create large amounts of export income; because the level of production for portable computers in Korea is low, firms plan to export the screens to U.S. computer companies.

The drive to develop FPD manufacturing capabilities in Taiwan appears to be related to its role as a home for personal computer manufacturers. Taiwanese companies have an even greater share of the world computer monitor market (approximately 50 percent) than do Korean firms, and have a growing share of the portable computer market. In 1993, earnings from notebook PC production exceeded those for desktop PC production, and one source estimates that one-quarter of all notebook computers produced in 1995 will be made in Taiwan.[10] However, during 1993, an insufficient supply of LCD screens meant that Taiwanese producers were unable to fill many orders; these firms appear determined to become more independent of FPDs supplied by Japan.

An issue that firms in both nations must address is the lack of a materials and equipment infrastructure; most inputs are imported from Japan. Acquiring such inputs from other nations allows the new producers to take advantage of the technology embodied in the inputs. However, it also keeps

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[6] David Mentley, Director, Display Industry Research, Stanford Resources, Inc., San Jose, CA, personal communication, Mar. 21, 1995.

[7] Data from the Japanese Ministry of International Trade and Industry, cited in Department of Defense, "Building U.S. Capabilities in Flat Panel Displays: Report of the Flat Panel Display Task Force," October 1994, p. IV-2.

[8] Tomohaku Nakamori, "Korea and Taiwan Furiously Pursuing Japan in TFT-LCD," *Nikkei Electronics*, May 23, 1994, pp. 125-134 (translation in *JPRS Report: Science & Technology Japan*, Mar. 15, 1995).

[9] Yoichi Funaki and K. Nozaki, "Korean Yield Shows Remarkable Growth; Taiwan's Production Moves Toward Stable Supply," in *Flat Panel Display 1995*, op. cit., footnote 1, pp. 109-112.

[10] See David Lieberman, "Taiwan Lags in Active-Matrix LCDs," *Electronic Engineering Times*, Oct. 17, 1994, p. 27; Funaki and Nozaki, op. cit., footnote 9; and Scott McCartney, "Small Companies Gain Ground in Notebooks by Buying From Taiwan," *Wall Street Journal*, June 1, 1995, p. B1.

TABLE 2-4: Announced Liquid Crystal Display Investments by Korean Firms (in millions of dollars)

Company	Investment
Samsung	1,250
LG Electronics	875
Hyundai	575
Daewoo-Orion	550

SOURCES: Nikkei *Microdevices* data, cited in William C. O'Mara, "Active Matrix LCD Manufacturing," in *1994 SID International Symposium Seminar Lecture Notes* (Santa Ana, CA: Society for Information Display, 1994), vol. 1, p M-3/19; "South Korea. Industry Planning Major Drive Into LCD Market," *FBIS Science & Technology Perspectives*, Feb. 28, 1994, "ROK Moving 'Full Scale' Into Next-Generation Display s," *Pacific Rim Economic Review*, June 29, 1994, pp. 25-26; and Laxmi Nakarmi, "Look Out World—Samsung Is Coming," *Business Week*, July 10, 1995, p. 52

the cost of production high because spending on FPD manufacturing equipment and components (driver chips, color filters, and backlights) comprises the majority of FPD manufacturing costs.

To gain access to leading-edge technology, Korean firms have relied on technology transfer agreements with second-tier Japanese firms and some American firms. Samsung has taken several such steps, including forming an alliance with Toshiba in 1993 to develop LCD integrated circuits; signing a cross-licensing agreement with Fujitsu; and, through the joint venture Samsung-Corning, constructing a color filter factory expected to have an annual capacity of 1.5 million 10-inchfilters.11 Hyundai is a majority owner of ImageQuest, a California firm formed in 1992 with American researchers. LG Electronics (formerly Lucky-Goldstar) formed a $100-million *joint research corporation* with the Japanese company Alps Electric in 1994, and also has a technology agreement with Hitachi.[12] Orion Electric, a subsidiary of the Daewoo Group, has a technology transfer agreement with Toshiba for PMLCDs. Orion has announced plans to invest in AMLCDs in 1995.

Samsung is the most experienced LCD producer, having begun production of PMLCDs in 1984 and AMLCDs in 1993. It was the first Korean company to mass produce AMLCD screens for notebook computers, and has produced displays as large as 14 inches. LG Electronics and Hyundai began PMLCD production in 1988 and 1990, respectively; LG will begin mass production of AMLCDs later this year, and Hyundai is transferring AMLCD technology from ImageQuest to a line in Korea. Announced investments in LCD manufacturing by these firms exceed those of some of the lower tier Japanese firms (see table 2-4).

Monthly production of notebook-size AMLCDs in Korea (primarily by Samsung and LG Electronics) is expected to reach 150,000 screens by the end of 1995. [13] Hyundai expects to produce approximately 30,000 displays per month beginning in 1996. in Taiwan, mass production is scheduled to begin in 1997 (see table 2-5). There are several manufacturers of PMLCDs in Taiwan, including Picvue, Nan Ya Plastics, and Chung-Hua Picture Tubes. AMLCD production has been led by Unipac and PrimeView International, both of which are producing AMLCDs up to 6 inches in diagonal and are carrying out pilot production of notebook screens. There have been mixed reports on the progress of these firms toward volume production, citing difficulties in attracting skilled engineers and in maintaining access to components. *4

[11] "ROK Moving 'Full Scale' Into Next_ Generation Displays," *Pacific Rim Economic Review*, June 29, 1994, p. 26; "Fujitsu, Samsung Agree To Exchange LCD Technology, ''Nikkei *Weekly*, Apr. 17, 1995, p. 22.

[12] "Goldstar Signs New Foreign Technology Agreements," *Maeil Kyongje Sinmun*, June 21, 1994, pp. 1 , 4 (summary in *Pacific Rim Economic Review*, Sept. 21, 1994); "South Korea: Liquid Crystal Display Assessed," *FBIS S&T Perspectives*, vol. 10, No. 3, Mar. 31, 1995, pp. 18-19.

[13] "South Korea's Top Three Device Makers Investing Heavily in TFT LCD Technology," *Channel*, vol. 8, No. 4, May 1995, p. 18.

[14] Mark Carroll, "Taiwan Displays LCD Woes," *Electronic Engineering Times*, May 29, 1995, pp. 18,22.

TABLE 2-5: Production Lines for 10-Inch Diagonal AMLCD Screens in Korea and Taiwan

Company	Plant location	Substrate size (mm)	Date operational	Initial capacity (substrates/ month)	Full capacity (substrates/ month)
Samsung	Kihung	370 x 470	Dec. 1994	15,000	80,000
LG Electronics	Kumi	370 x 470	Nov. 1995	40,000	80,000
Unipac	Taiwan	320 x400	Mar. 1997	n/a	n/a
PrimeView International	Taiwan	370 x 470	Dec. 1997	24,000	n/a

KEY: AMLCD = Active Matrix Liquid Crystal Display

SOURCES: David Lieberman, "Taiwan Lags in Active-Matrix LCDs Electronic Engineefing *Times,* Oct 17, 1994, p 27, "Scale of Liquid Crystal Industry Assessed," pp. 74-80, chart 3, and Funaki Yoichi and K. Nozaki, "Korean Yield Shows Remarkable Growth, Taiwan's Production Moves Toward Stable Supply," pp. 109-112, table 1, both in *Flat Panel Display* 1995, Nikkei *Microdevices,* Dec. 9, 1994 (translation provided by Maurice Cloutier, Foreign Broadcast Information Service), "South Korea's Top Three Device Makers Investing Heavily in TFT LCD Technology, " *Channel,* May 1995, p 18

The Republic of Korea has designated displays a strategic industry, which allows tariff reductions on imported inputs and access to lower cost capital from abroad. The Ministry of Trade, Industry and Energy planned to fund display development through its Electro-21 program, but failed to do so; it has given only $6 million to an industry research consortium.[15] However, in June 1994, 'he Korean government announced that it would fund a *thin-film LCD* research program at a level of $156 million, and a program to develop *next-generation flat displays* at a level of $21 million. Both programs are multiyear efforts, with private support exceeding government funding.[16] Taiwan's Electronics Research and Service Organization (ERSO) has worked with companies to develop prototype FPDs, and has also been a source of trained engineers for companies such as PrimeView. ERSO projects have included research on AMLCD, plasma, and FED.[17]

in total, Korean firms have set a goal of reaching a 10-percent share of the world AMLCD market by the year 2000. Taiwanese firms are trying to develop an indigenous supply of notebook screens to lessen their dependence on foreign-made displays. If successful, these efforts will put a considerable amount of pressure on Japanese manufacturers to reduce prices.

Europe

The European share of the FPD market has been marginal to date; only in the production of plasma displays does it have a significant presence (13 percent of world production in 1994). The largest European FPD initiative is the Flat Panel Display Co. (FPD Co.), a joint venture between the Dutch electronics firm Philips NV, the French companies SAGEM SA and Thomson Multimedia, and the German chemical firm Merck (see figure 2-6). The company was formed in 1992 and is based in Eindhoven, the Netherlands. FPD Co. has sold tens of thousands of units, and has a goal of $100 million in global revenues in 1995.[18]

Philips is clearly the driver behind FPD Co., having built a pilot plant in Eindhoven in 1987 and planned for commercial production since 1991.[19] Philips has brought two assets to FPD Co.: 1) a process for using thin film diodes that it believes will provide better performance at a lower price than thin film transistor AMLCDs, and 2) a large integrated circuit fabrication plant near Eindhoven (the Maas facility), which had been

[15] Andrew Pollack, "From Korea, a Challenge to Japan," *New York Times,* May 12, 1994, p. D1 .

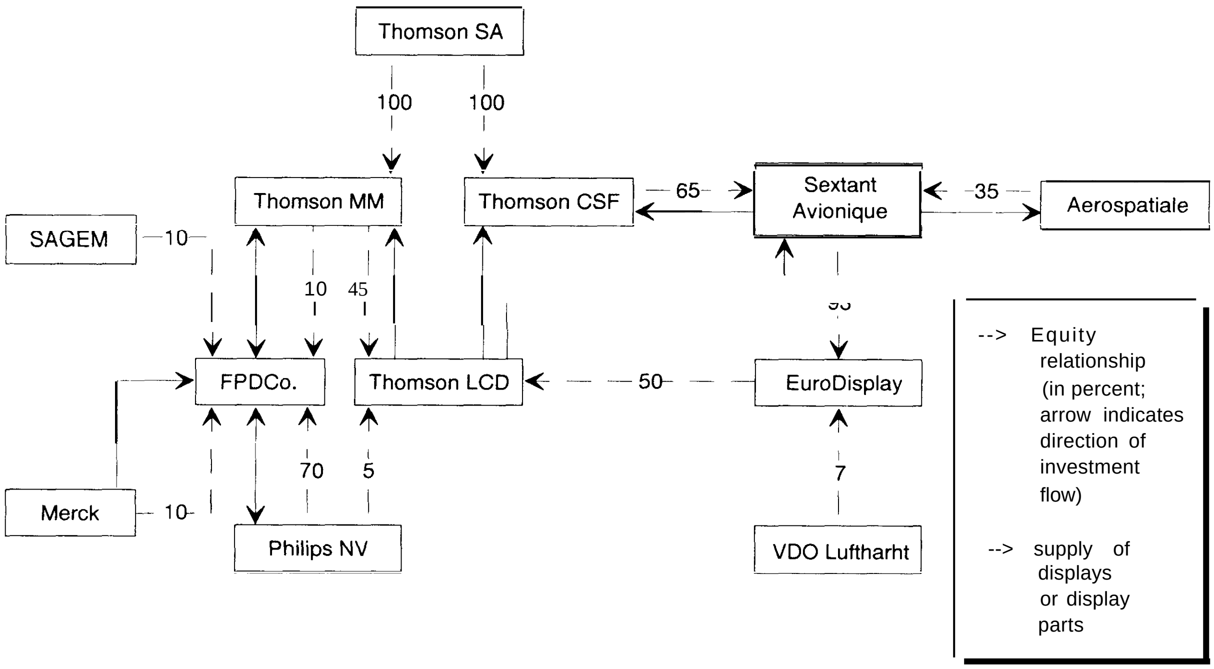
[16] "Government-Supported Electronics Projects Outlined," *Pacific Rim Economic Review-South Korea,* July *28, 1994.*

[17] Alan Patterson, "Taiwan Startups Eye LCDs," *Electronic Engineering Times,* Mar. 21, 1994, p. 26.

[18] Robert Gray, Product Engineer, FPD Co., San Jose, CA, persona] communication, June 5, 1995.

[19] Ronald van de Krol, "Rival Systems Attack Japan's Dominance," *Financial Times,* May 3, 1995, p. VI.

FIGURE 2-6: Supply and Ownership Relationships Among European Active Matrix Liquid Crystal Display Producers



KEY: FPD Co = Flat Panel Display Co ; SAGEM = Societe d'Applications Generales d'Electricite et de Mechanique; Thomson CSF = Thomson's aerospace and defense systems divisions; Thomson LCD = Thomson Liquid Crystal Display; Thomson MM = Thomson's multimedia and consumer electronics divisions.

NOTES: All percentages are rounded, Thomson SA is the parent company of Thomson MM and Thomson CSF, Philips NV is the parent of all Philips divisions,

SOURCES. Office of Technology Assessment, 1995, based on information from trade press and industry representatives

unused since Philips' Megaproject bid in the late 1980s.[20] By the end of 1994, FPD Co. had invested nearly $300 million for capital improvements to the plant. in 1994, the consortium announced that it was considering a second high-volume plant to be located in Taiwan, Singapore, or the United States.

The Maas facility's capacity has increased from 40,000 displays per month when commercial production began early in 1995 to 70,000 monthly; FPD Co. hopes to increase production to 75,000 per month by the end of 1995.[21] Along with a small pilot plant in central Eindhoven, FPD Co. may have a capacity as high as 100,000 displays per month. It will produce both display components and finished displays; diagonal sizes range from 2.8 to 10.4 inches, and larger displays are being developed.[22] Initially, it is concentrating on automotive, commercial projection, and airline entertainment system applications. Between 25

[20] Ronald van de Krol, "Europe's Liquid Assets," *Financial Times,* Dec. *22, 1994,* p. 10.

[21] van de Krol, op. cit., footnote 19; Gray, op. cit., footnote 18.

[22] Robert Hartman, Group Leader, FPD Co., Advanced Development Center, Eindhoven, Netherlands, personal communication, May 24, 1995; Leo Pekelharing, U.S. Representative, FPD Co., San Jose, CA, personal communication, Apr. 3, 1995.

and 30 percent of the displays are used internally by Philips and Thomson (primarily for HDTV and projection TV applications). The remainder of FPD Co.'s production is sold commercially in Europe, North America, and Asia.[23]

Although a distinct legal entity, FPD Co. receives significant administrative support from Philips, and shares research with all its parent companies. SAGEM has contributed technology to reduce the number of steps in thin film transistor (TFT) fabrication from between six and eight to two or three, thus allowing FPD Co. to develop TFTs in the future.[24] Merck supplies liquid crystals to the venture. Philips and Thomson are also important suppliers to, as well as customers of, FPD Co.; for example, Philips produces the backlight for FPD Co. displays.[25]

In addition to FPD Co., several Thomson SA enterprises are involved in FPDs (see figure 2-6). Sextant Avionique is Europe's leading manufacturer of avionic AMLCDs; its $700 million in total revenues is split almost evenly between civil and military aerospace. Its military sales are all made in Europe or to European manufacturers; sales in the United States are limited to commercial avionics.

All of Sextant's LCDs are supplied by Thomson LCD. Building on the Thomson-GE work from the 1980s, Thomson moved LCD operations from the United States to Grenoble, France. A small plant (annual capacity in the thousands) produces 8- by 8-inch displays for use by Sextant, and a new facility was recently completed to build 14- by 14-inch AMLCDs; although monitor-sized color prototypes have been built, the line has experienced production difficulties. In addition to supplying Sextant's needs, Thomson will use these displays internally.[26]

Thomson SA has expanded its plasma facility, which will have an annual capacity of approximately 5,000 displays. Although most panels are sold in France where they are used in police and military applications (rugged workstations), the company's U.S. operations sell plasma panels to equipment manufacturers and integrators, mostly small volumes (hundreds) of 13-inch displays for military, industrial, and medical applications. Thomson Multimedia has recently developed a 19-inch color plasma display prototype, with potential applications in professional workstations and HDTV.[27]

In FEDs, PixTech (formerly Pixel) of France is the leading firm. PixTech was formed in 1992 to commercialize developments in FED technology at the Laboratoire d'Electronique, de Technologie et d'Instrumentation (LETI), a research laboratory of the French atomic energy agency, which had built on work done at the American firm, SRI International. PixTech is pursuing spatial color FED technology and holds the rights to several cold cathode technology approaches. PixTech is planning to build a medium-volume production line (annual capacity of 50,000 or more) for 6-inch diagonal displays, and hopes to develop a 10.5-inch FED by the end of 1995. Completing the circle, PixTech has entered into alliances with Raytheon, Texas Instruments, Futaba, and Motorola, to share

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[23] van de Krol, op. cit., footnote 19.

[24] SAGEM transferred this technology from the French national telecommunications laboratory, CNET; see Richard L. Hudson, "Philips Refits Dutch Plant in Bold Plan To Unseat Rivals," *Wall Street Journal*, July 28, 1993, p. B4.

[25] Gray, op. cit., footnote 18.

[26] Larry Webster and Willy Moses, U.S. Representatives, Sextant Avionique, Miami, FL, personal communication, May 19, 1995.

[27] Ernest Stern, President, Thomson Components and Tubes Corp., Totowa, NJ, personal communication, May 19, 1995.

experimental quantities and cross-license technology.[28]

The European Union (EU) has supported some FPD R&D.[29] As part of the Third European Research and Technology Development Framework Program, the European Strategic Programme for Research and Development in Information Technologies (ESPRIT) devoted less than $50 million to cost-shared display research during the period 1990-94. The Fourth Framework Program, scheduled to last through 1998, has budgeted $128 million for displays. The main thrust is the European Consortium Active Matrix (ECAM), an industry-led project focusing on AMLCDs. Started in January 1993, the ECAM project involves a total of 19 partners from the Netherlands (Philips is the lead partner), France, Germany, the United Kingdom, and Belgium, and is composed of 11 projects. The overall aim is to develop technologies and components that will make larger display sizes and/or higher resolutions feasible, increase the number of potential applications of LCD technology, and develop less complex designs and more cost-effective production methods. Smaller projects focus on FEDs and ferroelectric LCDs.

While European entities are currently niche players, the coordination provided by EU involvement and the interlocked investments by large electronics firms could allow European companies to increase their share in plasma and AMLCDs, and to lead the commercialization of FED.

EFFECTS ON RELATED INDUSTRIES

Development of a domestic FPD industry could benefit related industries—both users and suppliers—but there is considerable uncertainty regarding the size of those benefits. The presence of domestic sources could enable U.S. firms competing in industries that use FPDs in their products (so-called *downstream* industries such as portable computer manufacturers) to work more closely with suppliers of a critical component that accounts for a large fraction of the product's value and appeal to the customer. Collaborating with foreign-based suppliers is difficult for some firms, and there have been periods of undersupply of FPDs in the past. However, most firms have supply arrangements with several producers, and the current and proposed production capacity appears sufficient to meet demand in the near future.

Additional integration of system functions onto the display could also affect downstream industries by putting display manufacturers in a stronger position relative to the system manufacturers. There are several technical paths such integration could take, but to date there has been limited integration in high-volume production. Finally, related industries, such as semiconductor devices, could benefit from developments in a high-volume domestic FPD industry. There are several areas in common—largely in equipment and materials inputs—between FPD production and semiconductor device manufacturing. But significant differences in the actual production processes and in the size of the two industries will limit such effects.

Downstream Industries

Some observers argue that, for diversified products based on advanced FPDs, the lack of a domestic FPD manufacturing base could inhibit competitiveness. Sometimes, the FPD serves to differentiate the downstream product. In such cases, it is important for the downstream firm to be able to purchase the best FPDs available or to have custom designs made. Since many Japanese

[28] Bob Taylor, Manager, Flat Panel Displays, Texas Instruments, Dallas, TX, personal communication, Apr. 17, 1995; Hambrecht & Quist and Needham & Co., Inc., *PixTech Prospectus*, July 18, 1995.

[29] "Exploitation Within the ESPRIT Programme," *Euro Abstracts*, No 32, May 1994, p. 303, reprinted in *JPRS Science & Technology Europe/International Economic Competitiveness*, JPRS-EST-94-017-L, July 11, 1994; Ken Werner, "U.S. Display Industry: On the Edge," *IEEE Spectrum*, May 1995, pp. 62-69.

FPD producers are vertically integrated electronics companies, their first priority could be to supply displays needed for the firm's own end products, forcing U.S. firms that make competing end products to wait longer for the latest displays. A strong U.S. FPD industry would make downstream U.S. firms much less dependent on Japanese FPD producers.

In some products, the best design might require, for example, a different size display, a new way of fitting the display into the product housing, or a special electronic interface between the display and other components. Japanese dominance of the FPD industry could pose difficulties for U.S. firms. In many cases, Japanese FPD producers have not been interested in customizing displays to U.S. customers' specifications, particularly for small numbers of displays. This is particularly true in military displays, which are required in custom versions and in small quantities; Sharp Corp., for one, has refused to deal directly with DOD requirements for FPDs.

In addition, relying on Japanese display producers who might use display designs to produce competing products could put U.S. customers at a competitive disadvantage. In cases where specialized requirements must be designed into the display, U.S. firms may hesitate to share sensitive product development information with companies that are also downstream competitors. The best known example of this problem is the Wizard, a personal digital assistant (PDA) introduced by Sharp soon after Apple's Newton, which Sharp produced for Apple.

However, there are ways for downstream users to limit the flow of design information. Computer companies typically protect their designs by using rigorous nondisclosure agreements with their FPD suppliers. These are used to limit the flow of design information to competitors, including those within the same corporate group as the display manufacturer. This seems to provide adequate protection, and the growth in FPD manufacturing capacity will ease these concerns somewhat by giving U.S. firms more choices. Increasing competition in the market for standardized FPDs could make some firms more willing to work on custom designs.

The only domestic downstream firm that has moved to gain direct control over FPD production is IBM, whose Japanese subsidiary is a joint owner of Display Technology Inc. (DTI), a leading FPD manufacturer located in Japan. This approach allows IBM to vertically integrate FPD production with portable computer manufacturing, but it has to cooperate in display design and production with its co-owner, Toshiba, a competitor in portable computers. Aside from IBM, leading U.S. portable computer manufacturers (such as Compaq, Apple, and Texas Instruments) rely on multiple sources of display manufacturers to supply relatively standardized computer screens.

These issues are of most concern in custom sectors of the FPD market. Sharp has been a pioneer in developing new applications for FPDs, utilizing its core capabilities in LCD production to create new products. Sharp used LCDs to create PDAs and a large-format videocamera viewfinder, as well as to enter the portable computer market. However, there are several characteristics of the largest segment of the FPD market—LCDs for portable information systems—that place it toward the commodity end of the spectrum. This suggests that although downstream users may benefit from the development of a domestic, high-volume, manufacturing capability, the benefits could be limited to the smaller segments of the market in which display customization is required.

In the market for portable computer displays, FPDs are becoming more like commodity items. The majority of FPD plants in operation or under construction are designed to produce screens suitable for notebook computers. While there have not been strict product definitions, the standard screen for this application has evolved from an 8.4-inch diagonal VGA (video graphics adapter, a standard for computer displays that is an array of information comprised of 640 rows and 480 columns) in the early 1990s, to a 10.4-inch VGA screen in 1994, to what is becoming the new standard, 10.4- or 11.3-inch SVGA screens (super-

VGA, 800 by 600 pixels) that display 16.7 million colors. Some XGA screens (extended graphics array, 1024 by 768 pixels) have also been produced. Other than screen size, resolution, and color palette, there do not appear to be any strong distinguishing characteristics from the consumer's perspective.

Manufacturing considerations reinforce the standardization of display types. Like integrated circuits (ICs), manufacturing costs for standardized displays decrease with increasing cumulative production of that item: the more screens produced, the less each costs to produce. The rate of cost reduction for AMLCDs has been estimated at half of that for ICs.[30] To a large extent, the slower rate of cost reduction in AMLCD production is attributable to the difficulty in producing what are effectively large-area ICs on glass substrates. Display production has proven more difficult than manufacturing semiconductor chips. Large amounts of production have brought the yield—percentage of useable displays—to 70 percent, compared with semiconductors, where yields are typically greater than 90 percent. Combined with the large capital costs required for a state-of-the-art production facility, this trend rewards high production volumes of a similar product; creating customized versions of a display increases the cost of manufacturing on that particular production line.

Manufacturing costs have been steadily reduced, however, and resulting decreases in display prices have reinforced the trend toward commodity displays. One analyst estimates that manufacturing costs in Japan for 10-inch AMLCDs declined from $2,500 in 1991 to just over $1,000 in 1993; during the same period, manufacturing yields increased from 10 percent to nearly 60 percent.[31] During 1993, AMLCD prices quoted by Japanese producers declined by approximately 17 percent; they fell by as much as 20 percent during the first three quarters of 1994, and by 25 percent during the last quarter.[32] In dollar terms, prices fell from $1,200 in mid-1994 to $830 in early 1995.[33]

The principal cause of the rapid decline in prices was the increase in productive capacity during 1994 as new manufacturing facilities were brought online by Sharp, NEC, DTI, and other firms; one source estimates that Japan's total monthly LCD output has increased 62 percent since 1994.[34] The increase in AMLCD production, combined with price pressure from improved PMLCD screens, has resulted in diminishing profits for AMLCD manufacturers.[35] Growing production capacity will drive the prices of standard displays down further. In the early years of mass production of AMLCDs, manufacturing was concentrated among a few firms in Japan.

[30] Historical estimates for integrated circuits show a 28-percent decrease in unit cost for each doubling of production volume. See U.S. Congress, Office of Technology Assessment, *International Competitiveness in Electronics*, OTA-ISC-200 (Washington, DC: U.S. Government Printing Office, November 1983), p. 76. DOD has estimated the slope for AMLCDs to be 14 percent; Kenneth Flamm, DOD, presentation to OTA, May 18, 1995.

[31] William C. O'Mara, "AMLCD Manufacturing," in *1994 SID International Symposium Seminar Lecture Notes* (Santa Ana, CA: Society for Information Display, 1994), vol. I. Another analyst estimates that yields are currently greater than 70 percent; Joseph Castellano, Stanford Resources, Inc., San Jose, CA, personal communication, Apr. 14, 1995.

[32] Japanese fiscal years; for historical prices, see "Scale of Liquid Crystal Industry Assessed," op. cit., footnote 1, figure 4A. For recent prices, see Wakabayashi, op. cit., footnote 2, figure 1. Also see estimates from *Nihon Keizai Shinbun*, quoted in Hisayuki Mitsusada, "Advanced LCD Makers Look Beyond PCs," *Nikkei Weekly*, Mar. 20, 1995, p. 8.

[33] U.S. prices from Brooke Crothers and Rob Guth, "Cheaper LCDs Spur Notebook Price Breaks," *InfoWorld*, Apr. 24, 1995, p. 1. Note that while displays represent the largest single component in a notebook computer, even as performance (resolution, size, and number of colors) has increased, screen prices have declined and are approaching those of microprocessors.

[34] Estimates from Merrill Lynch Japan, quoted in Mitsusada, op. cit., footnote 32.

[35] Wakabayashi, op. cit., footnote 2.

However, the industry structure is becoming less concentrated, and volume AMLCD production is being developed in Korea, Taiwan, and Europe.

In general, as products mature and become commodities, the basis for competition shifts from product innovation to reduction of manufacturing costs and incremental improvements to performance. As this happens, production moves to lowest-cost mass manufacturers that are most able to offer standardized goods at steadily decreasing ratios of price to performance. As with dynamic random access memory chips (DRAMs, see box 2-2), successful entry by Korean and other firms will likely have the effect of opening up competition on pricing and availability of AMLCDs, which will have a salutary effect from the perspective of U.S. display users.

Integration of Displays and Systems

FPDs could become critical to electronic products if they incorporate functions that are presently elsewhere in the systems that use displays. Known as *integration*, this technology path would involve building increasingly sophisticated system functions into the display itself, so that—in the extreme case—the display is the system. Under this scenario, the location of display production would be more important because, in many cases, it will be the end product with little value added elsewhere.[36] Product competition would be design intensive, rather than manufacturing intensive, and could result in a more diversified set of FPD products. In such a scenario, the inability to produce displays domestically would handicap U.S. competitiveness in systems like portable computers because the lack of an FPD manufacturing base would limit the ability to produce integrated systems.

Integration comprises a spectrum of design and manufacturing choices. The primary forms of integration are electronic, but there are also mechanical or functional forms; for example, designing the display frame and system cover in notebook computers as one structure to reduce weight and size.[37] The range of possibilities for electronic integration extends from complete integration at one end to a bare display, which has only the electrodes that supply current, at the other. In the latter case, there is no integration: circuitry that drives the display, as well as the circuitry and mechanical devices for the system of which the display is a part, is located elsewhere in the system.

Electronic integration can be achieved in two ways. One way is to mount IC chips onto the display glass. This method has been used for driver chips (ICs that are the first level of interface between the display and the system), which improves the manufacturing process. Using such a method to achieve higher levels of integration—such as integrating sophisticated ICs like microprocessors or memory chips—is complicated by limited space on the display glass, the complexity of interconnections for such chips, and differences in the product development cycles of ICs and FPDs. While these complications may be overcome, it is not clear that FPD manufacturers will have an advantage over computer manufacturers in the integration of nondisplay functions.

The second method of achieving integration is to extend the techniques used to build active matrix circuits—TFTs on glass—to more sophisticated circuits required by memory or microprocessor functions. There are several technical barriers to this approach, however, and the circuit density required may be hard to attain with TFTs. In addition, mastery of AMLCD manufacturing has been difficult for the leading firms, who

[36] For a discussion of the potential strategic implications of integration, see Michael Borrus and Jeffrey A Hart, "Display's the Thing: The Real Stakes in the Conflict Over High-Resolution Displays," *Journal of Policy Analysis and Management*, vol. 13, No. 1, 1994, pp. 21-54.

[37] Steven Depp, Director, Subsystem Technologies and Applications Laboratory, Thomas J. Watson Research Center, IBM, Yorktown Heights, NY, personal communication, Apr. 11, 1995.

BOX 2-2: Dynamic Random Access Memory (DRAM) Chips

in examining the potential effects of foreign dominance of flat panel display (FPD) production on related and downstream U.S. industries, it is instructive to consider experience with the semiconductor industry over the past decade, in particular, the movement of leadership in production of dynamic random access memories (DRAMs) from the United States to East Asia is relevant,

During the 1980s, declines in the competitiveness of U.S. DRAM producers relative to Japanese competitors led to concerns for the semiconductor industry, First, it was asserted that loss of dominance in DRAMs would harm manufacturing competitiveness in other integrated circuit (IC) products because DRAMs were thought to be a technology driver for IC manufacturing as a whole Second, it was argued that declines in domestic DRAM market share would hurt the competitiveness of downstream industries, such as computers, Third, some observers were concerned that the shift in DRAM leadership to Japan would be followed by loss of leadership in production of semiconductor manufacturing equipment.

During the period from 1978 to 1986, Japanese firms' share of world DRAM production increased by roughly 60 percent, mostly at the expense of US firms; more recently, a large fraction of production has been captured by firms in South Korea and Southeast Asia. [1]Concerns over the loss of leadership in DRAM production led to a consortium (U.S. Memories) to offset the dominance of Japanese DRAM producers, However, the consortium was abandoned after the entry of low-cost Korean manufacturers caused a supply glut that resulted in multiple sources of supply and falling prices,

Although DRAM production for the merchant market (that is, through arms-length sales to electronics manufacturers) has largely moved to Japan and South Korea, captive production (to satisfy internal company demand) by firms such as AT&T and IBM has continued at a substantial level As the capital investment required for a DRAM plant has increased, even these large firms have entered into joint production agreements; for example, IBM, Siemens, and Toshiba are collaborating on 256-megabyte DRAM production technology,

Concerns over the strategic nature of DRAMs also contributed to the creation of Sematech in 1987, Although the consortium abandoned its original goal to develop production processes for memory chips and other ICs, it moved to supporting the development of a semiconductor supplier base. While there is debate over the effectiveness of Sematech, most consider it to be successful, and the U.S. firms recently regained leadership of semiconductor production,[2] in the semiconductor supplier industry, domestic firms have also improved their position, After declining from 1981 to 1990, domestic equipment manufacturers have increased their share of the world market to nearly 54 percent in 1994.[3]

Although U.S. production of DRAMs has remained at roughly 20 percent market share since the late 1980s, U.S. producers regained the lead in worldwide semiconductor market share in 1993, largely by recapturing shares of expanding markets in products such as microprocessors and application-specific

(continued)

[1]For historical market shares, see U.S. Congress, Office of Technology Assessment, *Contributions of DOE Weapons Labs* and *NIST to Semiconductor Technology,* OTA-ITE-585 (Washington, DC: U.S. Government Printing Off Ice, September 1993), figure 3-5 South Korean companies currently produce roughly 30 percent of DRAMs, and some analysts predict they will surpass Japanese production; see David Hamilton and Steve Glain, "Koreans Move To Grab Memory-Chip Market from the Japanese, " *Wall Street Journal,* Mar, 14, 1995, p Al,

[2]For a critical view of Sematech, see "Uncle Sam's Helping Hand, " *The Economist,* Apr. 2, 1994, p 77

[3]Semiconductor Industry Association, *The Information Highway: Paved with Silicon,* March 1995, p 5,

BOX 2-2: Dynamic Random Access Memory (DRAM) Chips (Cont'd.)

integrated circuits (ASICs).[4] Despite initial fears, the wide availability of low-priced DRAMs in recent years demonstrates that end-users in the United States can benefit from increased international competition. For example, many U.S. firms are competitive in personal computer manufacturing. This may also be the case in the commodity segments of the FPD market.

FPDs and semiconductors both comprise a spectrum of device types that are typically sold to downstream users such as computer, communications, and consumer electronics manufacturers. The semiconductor industry produces a wide variety of integrated circuits (ICs), ranging from DRAMs--devices whose production requires a large capital investment, but are basically commodity items—to ASICs that are highly diversified products. Microprocessors—which are design-intensive and require large investments in manufacturing technology, but are produced in standard types within each product generation-fall somewhere between DRAMs and ASICs. An analogous description of the FPD industry would place standardized AMLCDs for notebook computers toward the commodity end, and complex custom AMLCDs, which have row-and-column drivers integrated onto the display, at the diversified product end. in between are the largest market segments (in value terms) —video displays for portable computers, communications devices, and games—that use both AMLCDs and PMLCDs.

There are limitations to the analogy, however. Perhaps the biggest difference is that in semiconductors, U S firms led the world in production before the loss of market share in commodity chips; in FPDs, the U.S. industry has lagged firms in Japan. Thus, rather than moving from commodity to higher value products, U.S. firms must either jump directly into production of diversified FPDs, or face entrenched competition in the large segments of the market moving toward commodities.

SOURCE Office of Technology Assessment, 1995

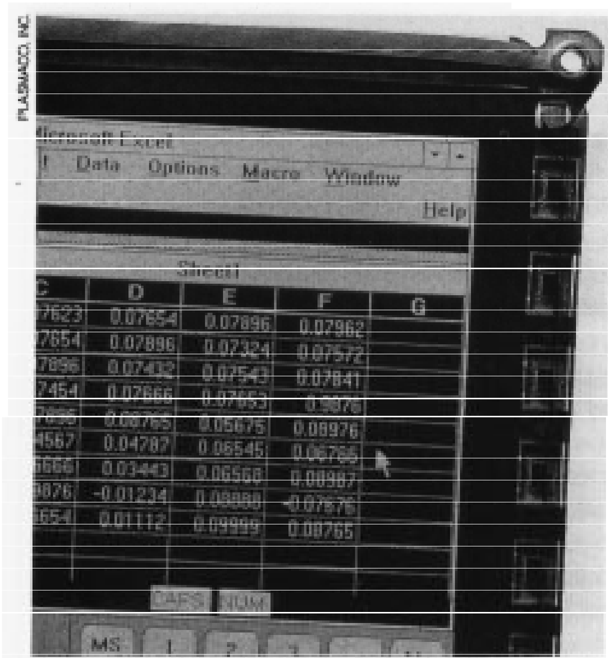
[4] For example, after declines in the early 1980s, U.S. share of the world market for microcomponents increased from approximately 50 percent in 1986 to just under 70 percent in 1992, and U S share of ASICs increased from less than 50 percent in 1988 to 53 percent in 1992, ibid., p 1, and U S. Congress, Office of Technology Assessment, op cit., footnote 1, figures 3-6 and 3-7.

suffered through several years of production at low yield levels. There is reason to conclude that including extra components on the display will only diminish yields.

Integrated Circuit Mounting Techniques

in the original method for attaching driver chips, called *chip-on-board* (COB), they are mounted on printed wiring boards that are connected to the display by metallic electrodes printed on a flexible substrate. The connector is mechanically joined to the row-and-column electrodes. Currently, the most common technique is *chip-on-film* (COF), also called *tape automated bonding* (TAB), in which bare (unpackaged) chips are mounted on a flexible tape (often made of selectively conductive rubber that has electrodes printed on it) for connection to the rows and columns. COF/TAB enables narrower spacing than COB and, by eliminating the chip packages, reduces volume and weight.

in the most advanced method of attaching chips to the display, called *chip-on-glass (COG),* bare chips are mounted directly onto the edges of the display glass substrate and connected directly to the electrodes. This method is the ultimate form of integration using discrete driver chips; it can reduce the FPD volume and weight further, while increasing the reliability of the connections between the drivers and the electrodes. The tradeoff



Chip-on-glass technology as seen on the edges of this plasma display, reduces manufacturing costs, improves reliability and decreases package size.

with COG is that it is difficult to repair faulty chips once they are mounted, and space is required around the edge of the display glass to mount the chips (which is counter to the design trend of minimizing the area of the display glass).

Currently, the primary items mounted using COF/TAB and COG are driver chips. The potential exists for other components, such as graphics controller and power conversion circuits, to be mounted in a similar fashion, but this has not yet occurred.

In general, emissive displays offer greater potential for integration via COG techniques. The back surface of the display glass is not utilized (unlike transmissive displays such as LCDs, in which the back surface of the glass must be left unobstructed so that light can pass through), thus providing a large surface for mounting chips; the difficulty is in making interconnections from the back. FED developers are also investigating multilayer ceramic modules that embed the display on one side of the substrate and chips on the other.

Depositing Silicon on Glass

A higher level of electronic integration is to fabricate electronic devices on the periphery of the display using the same or similar techniques used to fabricate active matrix elements.[38]

As with mounting chips on the display glass, there are limitations to this type of integration. Amorphous silicon—the most commonly used material for TFTs--is not well suited to the high-speed operation required for driver circuits, although a research group recently produced an experimental version of art amorphous silicon AMLCD with integrated drivers.[39]

Use of polycrystalline silicon could allow devices to operate at higher speeds and enable the fabrication of denser circuitry along the periphery of the display. Although similar in some ways to amorphous silicon fabrication, polycrystalline silicon typically requires deposition temperatures of 600 “C or more, compared to the 450 C maximum in amorphous silicon processing.[40] The higher temperatures require the use of quartz substrates rather than glass, which expands or breaks down at high temperatures. Quartz is more expensive than glass and limited in diameter to a few inches, thus limiting the application of polycrystalline silicon to small displays such as videocamera view finders and head-mounted displays. Anew glass developed by Corning that can with-

[38] An early expression of the concept of display integration can be found in T. Peter Brody and Paul R. Malmberg, ’’Large Scale Integration of Displays Through Thin-Film Transistor Technology,’’ International Journal of Hybrid Microelectronics, vol. 2, 1979, pp. 29-38.

[39] R. G. Stewart et al., “Circuit Design for a-Si AMLCDs with Integrated Drivers," p. 89, and H. Lebrun et al., “AMLCD with Integrated Drivers Made with Amorphous-Silicon TFTs,”p. 403, in 1995 SID International Symposium Digest of Technical Papers, vol. 26 (Santa Ana, CA: Society for Information Display, May 1995).

[40] Recent research has demonstrated methods for reducing the deposition temperature for polycrystalline Silicon to the same as amorphous silicon; see “Hitachi Advances in Low-Temp TFTs" Electronic Engineering Times, Oct. 17, 1994, p. 20.

stand temperatures as high as 600 °C may enable polycrystalline silicon processes to be adopted more widely.[41]

Single crystal silicon can also be used for making TFTs and other circuit elements. This process, pioneered by Kopin Corp., has the highest electronic performance of all. A standard IC is fabricated on a silicon wafer, and then stripped off and reattached to the glass panel of an FPD. This allows the active matrix and other integrated elements to be fabricated using proven semiconductor techniques. The display size is currently limited to approximately one-inch diameter devices, used in head-mounted and projection systems, and production is still in the prototype stage.

Spillover to Semiconductor Manufacturing

Similarities between the semiconductor and FPD industries have led to some synergy between their associated materials and equipment suppliers. For example, Semiconductor Equipment and Materials International (SEMI), which represents a large part of the world industry, has an FPD division with over 100 member companies. Such synergy could result in spillover effects, especially if the FPD industry were to become large compared with semiconductors. Some aspects of FPD production will likely place demands on equipment and materials suppliers that exceed requirements posed by IC manufacturing.

In addition to common materials and equipment inputs—such as semiconductors, gases, and deposition and photolithographic systems—some aspects of FPD manufacturing have much in common with semiconductor fabrication; the creation of hundreds of thousands of switching transistors, involving the deposition of semiconductors, metals, and insulators in multiple, repeated photolithography steps onto a silicon substrate.[42] Indeed, the earliest AMLCD fabrication lines were modified semiconductor lines, and, initially, there were spillovers between IC and FPD manufacturing. IC producers in Japan and Korea leveraged their semiconductor production experience in entering AMLCD manufacturing. Due to growing differences in production and markets, however, spillovers are likely to be limited mostly to the supplier level of the two industries. Thus, IC manufacturers are not likely to face competition from FPD producers, but IC fabricators that purchase equipment from FPD suppliers will have access to leading-edge technology that may not otherwise be available.

Despite the strong current and projected AMLCD growth rates, the FPD industry as a whole will likely remain a fraction of the size of the semiconductor industry (although some equipment and materials suppliers rely on FPDs for a large fraction of revenues). Worldwide revenues for semiconductor sales were $100 billion in 1994, compared with $9.33 billion in FPD sales. Semiconductor sales are projected to reach $200 billion by the year 2000, compared with the $20 billion projected for FPDs.[43] Given the larger potential market, equipment and materials suppliers for the semiconductor industry will have incentive to develop the needed tools, whether or not there was an FPD industry driving some of the technological developments.

Even in the absence of a high-volume domestic FPD industry, firms that supply equipment and materials could sell to foreign FPD manufacturers. U.S. firms that supply FPD and semiconductor manufacturers have made inroads in supplying foreign-based producers in Asia, such as Applied

[41] The previous standard, Corning code 7059, has a strain point, or temperature limit, of 593 °C; the new glass, Corning code 1737, has a strain point of 666 °C. See Dawne M. Moffatt, “Flat Panel Display Substrates,” in *Flat Panel Display Materials*, J. Batey, A. Chiang, and P. H. Holloway (eds.), Symposium Proceedings, vol. 345 (Pittsburgh, PA: Materials Research Society, 1994), p. 163.

[42] Borrus and Hart, op. cit., footnote 36.

[43] Semiconductor sales data and projections from Semiconductor Industry Association, *The Information Highway: Paved with Silicon*, March 1995, p. 1.

Materials (chemical vapor deposition), Photon Dynamics (testing), Corning (glass), and Texas Instruments (driver chips).

Spillover in Equipment and Materials

There are several areas in which FPDs drive semiconductor manufacturing processes, such as large area substrates and contamination problems. FPD manufacturers must have the capability to handle and process large substrates, currently up to 24 inches on a side, all while minimizing contamination. Semiconductor manufacturers are currently planning to move to 300-millimeter wafers (approximately 12 inches in diameter) from which the individual chips are made. The increased diameter requires larger handling equipment and processing chambers, and the increased surface area requires more stringent control of contamination. Both have been concerns for FPD manufacturers and suppliers.[44]

Another example is research on TFTs that has resulted in the creation of memory devices made out of polycrystalline silicon, with the potential for application to ICs. Researchers have also investigated the use of amorphous silicon to fabricate ICs; and atomic layer epitaxy, a thin film process developed to build EL displays, has been suggested as an alternative to current semiconductor processes.[45]

In other areas critical to semiconductor manufacturing, such as research on increasing the resolution of lithography systems, FPDs are not likely to be a driver for manufacturing technology. Semiconductor chip design and manufacturing constantly move toward narrower linewidths (the minimum feature size that can be deposited using semiconductor processing techniques) to fit more circuits onto a given chip size. The size of FPD pixels is fixed by the resolving capability of the human eye, and larger overall display sizes (containing more pixels) are the goal for FPD design and manufacturing.

Spillover in Production

While they share equipment, materials, and some process steps, the economics and market sizes of FPD manufacturing are different from those in semiconductor device manufacturing. Semiconductors are generally fabricated on silicon wafers in sets of roughly 100 chips. Each is about one centimeter across, can be tested before final packaging, and has little value in its unpackaged state. FPDs are fabricated on glass substrates that must have high surface quality and are larger, more fragile, and more temperature-sensitive than silicon. For laptop-size screens, six finished display panels are typically yielded from each substrate; each must be nearly completed before testing, and represents a significant investment in materials and process time. As the direct spillovers between the two types of manufacturing are limited, separate corporate divisions and facilities are used for FPD and semiconductor manufacturing.

One exception to the differences in the two manufacturing processes is the digital micromirror device developed by Texas Instruments. In this display, miniature mirrors that are deposited as a part of an IC chip reflect light to form an image. The device is fabricated on standard semiconductor lines, and circuit elements are created along with the mirror array. In this case, there are direct spillovers between IC and FPD production processes.

NATIONAL SECURITY REQUIREMENTS

Although the military demand for FPDs comprises a small part of the overall display market, military applications use a variety of FPD technol-

[44] For example, Applied Materials Corp. developed a prototype production system for 300-millimeter integrated circuit substrates based on its FPD production tool. See Walter Andrews, "Equipment Vendors Gear Up for 300-Millimeter Wafers," *Electronic News/VLSI Research Report*, July 17, 1995.

[45] See Chappell Brown, "Polysilicon TFTs Used in E^2PROM Operation," *Electronic Engineering Times*, Nov. 21, 1994, p. 37; "Amorphous Silicon Shows Promise," *Electronic Engineering Times*, June 5, 1995, p. 39; and "ALE Process Resurfaces," *Electronic Engineering Times*, Feb. 27, 1995, p. 37.

ogies and have a wide range of requirements. In many cases, intensive design and *ruggedization* of FPDs (see box 2-3) are necessary to assure adequate performance in military environments. For platforms facing less stringent environments, existing commercial products may offer sufficient performance.

In general, DOD has three options for acquiring displays. It can purchase custom FPDs from domestic producers, commercial FPDs from domestic producers, or commercial FPDs from foreign producers. Currently, DOD relies on a combination of domestic custom and foreign commercial displays. The commercial displays are much less expensive, but require more ruggedization than custom FPDs.

Military programs base their choices of display on mission requirements and available budgets. The tradeoffs between commercial and custom displays for military applications center on price and performance; this issue is of particular importance for AMLCDs used in aircraft cockpits.

There is a sharp debate over the suitability of commercial AMLCDs in DOD applications; while some see custom AMLCDs as prohibitively expensive, others are not convinced that commercial displays can provide adequate performance. Currently, several programs are using foreign-produced commercial AMLCDs. Cost constraints are the primary factor in these decisions. However, some programs have utilized greater flexibility in AMLCD selection by determining requirements from the specific operational environment of the application, rather than from Military Specifications.

As AMLCD technology is adopted for increasingly demanding commercial applications such as avionic and automotive displays, the performance of commercial products will be better suited for military needs. As custom suppliers move into these markets and gain manufacturing experience, their costs will decrease. These two trends suggest a convergence of military and some commercial FPDs, particularly in AMLCDs.

Military FPD Applications

Military systems use several different FPD technologies (see table 2-6). To date, military FPDs have been used mostly in portable computers, handheld devices, and large area displays on submarines and surface ships. Cockpit avionics is likely to be the next major application for FPDs.[46]

The fundamental technologies used in military FPDs are the same as in the commercial market. However, military displays differ in the size and shape of the display, and the need to adapt the display to extreme operating environments, including a wide range of temperatures, ambient lighting, and shock. Military display manufacturers must produce design-intensive products specific to military systems. These characteristics do not give the manufacturer experience in commercial, large-scale manufacturing. Contractors that ruggedize and integrate standard commercial products into military systems perform very specialized steps to enhance and protect the basic display (see box 2-3).

Battlefield Systems

One group of military display applications is portable battlefield information and communication systems, which include portable and vehicular applications. There are more than 25,000 AMLCD portable computers and PMLCD handheld devices in the military.[47] More than 5,000 handheld terminal units with alphanumeric PMLCDs are used by forward observers for targeting calcula-

[46] For purposes of this section, discussion of military FPDs is limited to applications in military systems, rather than in standard office equipment.

[47] Roger Johnson, Senior Vice President, Science Applications International Corp., San Diego, CA, personal communication, July 13, 1995; since the early 1990s, AMLCDs have increasingly displaced EL and PMLCDs in these portable systems.

BOX 2-3: Ruggedization

Converting a flat panel display for use in a military system—which involves enhancing the integrity of the display to withstand extremes of temperature, shock, and vibration—is called *ruggedization.* The nature of ruggedization depends on the display technology used, the nature of the system, and its operating environment. Electroluminescent and plasma displays, for example, are much more resistant to shock and temperature variations than are liquid crystal displays LCDs Some systems, such as field-test equipment, are neither mission critical nor continuously exposed to strenuous conditions, others are, such as a tank commander's tactical display. One of the most demanding applications is a cockpit avionics display.

Cockpit displays must be readable in direct sunlight and resistant to large variations in temperature. in addition, some applications require that the display be compatible with Night Vision Imaging Systems.[1] The active matrix LCD (AMLCD) is the primary type of cockpit flat panel display, due to its exceptional performance in direct sunlight. However, this performance comes with a tradeoff: LCDs only perform well in a limited temperature range, thus requiring additional ruggedization to allow them to operate under temperature extremes.[2]

Both commercial and custom AMLCDs require a large amount of ruggedization, typically including heaters, redundant backlights, electromagnetic interference filters, shock- and vibration-resistant packaging, and drivers, polarizers, and electronic connectors capable of withstanding wide variations in temperature and humidity (see table below).

Means of Achieving Rugged Features in Active Matrix Liquid Crystal Displays

Feature	Achieved in display by	Achieved in external modification by
Brightness	larger aperture design	brighter backlight
Redundant light source	n/a	redundant backlight
Sunlight readability	black matrix and AR coatings	antireflective coatings
Driver integrity	chip on glass	stronger driver interconnects
Viewing angle	thinner cell	collimators and diffusers
Shock resistance	unit integrity by design	reinforcing LCD unit; covering glass
Vibration resistance	unit integrity by design	reinforcing LCD unit; covering glass
Cold resistance	liquid crystal materials	heaters on glass
Heat resistance	liquid crystal materials and polarizers	thermal design and extended temperature polarizers
Humidity resistance	bonding	bonding
Sand/dust resistance	bonding	bonding, filters, housing

SOURCE: Office of Technology Assessment, 1995, based on interviews with manufacturers and Integrators

(continued)

[1] This feature requires that pilots using monochrome night vision be able to distinguish levels of shading The current requirement IS for 64 levels, most commercial and some military AMLCDs have achieved 256 levels

[2] Low temperatures affect LCDs primarily in two ways 1) a reduction in response time and color gamut shift necessitates the need for heaters and programmable look-up tables, and 2) the backlight required for an LCD-based display must incorporate heaters in order to turn on at cold temperatures in addition, liquid crystal materials and polarizers often suffer Irreversible damage at temperatures above 90 °C.

BOX 2-3: Ruggedization (Cont'd.)

Ruggedizing a commercial AMLCD involves activities almost entirely external to the display itself.[3] Because many of the firms that ruggedize commercial displays use the same processes for military and commercial systems, they amortize costs across a large volume of units. For a custom AMLCD, ruggedizing is partially achieved through the design and fabrication process, but external modifications are still necessary. Although they use displays designed for military use, many firms that ruggedize custom displays do so in low volumes, resulting in higher costs for ruggedization for military use. Despite the greater amount of ruggedization necessary for a commercial display, the LCD unit itself accounts for between one-fifth and one-third of the finished display price in both custom and commercial displays, given the price premium for a custom display, ruggedized custom displays are quite expensive.[4]

However, custom AMLCDs are expected to deliver superior performance, largely through their ability to withstand extreme environments. Some in industry and the military argue that ruggedized commercial displays still will not withstand severe conditions experienced in some applications The failures of polarizer adhesives in high humidity and liquid crystal materials in very high temperatures are the most frequently cited problems. Inexpensive commercial displays could have shorter life cycles, boosting costs for redesign and replacement over those of custom AMLCDs that are likely to last longer [5]

However, some argue that extreme conditions are experienced only on rare occasions or only in high performance aircraft and can be addressed by modifications to operational procedures or system requirements. Many other military applications, in aircraft and other systems, do not have such severe operational environments and could use commercial off-the-shelf displays.[6] Commercial AMLCDs lead or equal their custom counterparts in several areas important to ruggedization, including use of a black matrix, chip-on-glass technology, and low-temperature-resistant liquid crystal materials.[7] in addition, a reduced design life using a ruggedized commercial display may actually be less costly and allow newer technology to be incorporated into platforms sooner. Finally, as the commercial market expands to address the needs and harsher conditions seen in the portable and automotive products, the level of ruggedization required for a commercial display will diminish.

SOURCE Office of Technology Assessment, 1995.

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[3] Randall E. Orkis, "F-16 Retrofit Application Using a Modular Avionics System Architecture and Color Active Matrix Liquid Crystal Displays, " *SPIE International Symposium on Optical Engmeering in Aerospace Sensing. Cockpit Displays Conference,* April 1994, and "An Improved Full Color F-16 A/B and F-16 C/D Multi-Function Display Using a Ruggedized COTS Active Matrix Color Liquid Crystal Display, " *SPIE International Symposium on Aerospace/Defense Sensing and Dual Use Photonics: Cockpit Displays II,* April 1995.

[4] Firms that ruggedize commercial AMLCDs available for $1,000 to $4,000 charge from $5,000 to $20,000 for the finished system To ruggedize a custom display costing approximately $12,000, the system price is in the range of $35,000 to $50,000 Increasingiy, custom display manufacturers and integrators are pursuing commercial options to help reduce costs, Dan Doyle, Director of Display Products, Electronic Designs Inc. , Westborough, MA, personal communication, Aug 3, 1995

[5] James Moore, Naval Air Defense Center (Ret), Warminster, PA, personal communication, July 5, 1995, Keith Toby, F/A-l 8 avionics Team Leader, Naval Air Warfare Center, Indianapolis, IN, personal communication, July 5, 1995, and Curtis Casey, Vice President, Optical Imaging Systems, Northville, Ml, personal communication, July 14, 1995

[6] Donald Pinsky, Interstate Electronics (Ret.), Costa Mesa, CA, personal communication, May 2, 1995, Roger Johnson, Senior Vice President, Science Applications International Corp., San Diego, CA, personal communication, July 13, 1995, Gary Broderson, Senior Electrical Engineer, Advanced Concepts, Naval Air Systems Command, Arlington, VA, July 17, 1995, Dan Hamilton, Ogden Air Logistics Center, Hill AFB, UT, personal communication, June 27, 1995, and Randall E Orkis, Principal Research Scientist, National Security Division, Battelle Memorial Institute, Columbus, OH, personal communication, May 5, 1995

[7] A black matrix within the LCD unit enhances sunlight readability, chip-on-glass technology improves line driver interconnects and active area size of the whole display Automotive displays now available from Sharp Corp have these features, Randall E Orkis, Principal Research Scientist, National Security Division, Battelle Memorial Institute, Columbus, OH, personal communication, July 25, 1995.

TABLE 2-6: Flat Panel Display Applications and Technologies in Military Systems

Military system	Display applications	Potential display technologies
Avionics	Cockpit displays in fixed-wing and rotary aircraft	AM LCD
Vehicular/shipboard	Navigation, situation, and weapons displays in tanks, ground vehicles, ships, and submarines	AMLCD, EL, Plasma
Portable	Helmet mounted displays, laptops, handheld devices, test equipment, communications equipment	AMLCD, PMLCD, EL
Workstations and presentations	Command and control displays, large tactical and map displays, simulation and 3-D systems	AMLCD and DMD projectors, Plasma

KEY: AMLCD = active matrix liquid crystal display; DMD = digital micromirror device, EL= electroluminescent display; LCD = liquid crystal display, PMLCD = passive matrix liquid crystal display

SOURCES: Len Zuga, *U.S. Military Display Markets: New Technologies, Upgrades, and Government Funding Brighten Market,* Report 5207-16 (Mountain View, CA: Frost & Sullivan, 1995), and Office of Technology Assessment, 1995

tions and communication, for example.[48] Such devices are lightweight, consume little power, and are relatively inexpensive. AMLCDs are used in portable computers for test and maintenance equipment; the Army has used 13,000 ruggedized portable computers in its Lightweight Computer Unit (LCU) program, which provides test, maintenance, and diagnostic units for tanks and aircraft. A commercial AMLCD, purchased from a foreign manufacturer, is being used for the LCU screen .[49] Ruggedization appears to have been satisfactory for these LCUs; because field units can be replaced easily, there are no major concerns regarding their failure.[50]

Several programs have been examining the suitability of AMLCDs, plasma panels, and EL displays for vehicular applications. Mobile multiple launch rocket targeting systems, which require large, rugged screens, have used EL and plasma displays. in the future, vehicular FPDs will display various video motion and graphic images in trucks, tanks, and ships, including infrared vision enhancement, fire control, and targeting data. Given the similarities to conditions that avionic systems are exposed to (high temperatures and bright ambient light), the AMLCD is currently the leading contender. Examples include the Driver Vision Enhancement and the Commander's Tactical Display for the Bradley Fighting Vehicle. Plans call for individual soldiers to wear helmet-mounted displays (HMDs) that use small, very-high-resolution AMLCDs or possibly active matrix EL displays. HMDs are high performance devices that will likely require custom manufacture; several domestic companies are developing this technology.

Large Area Displays

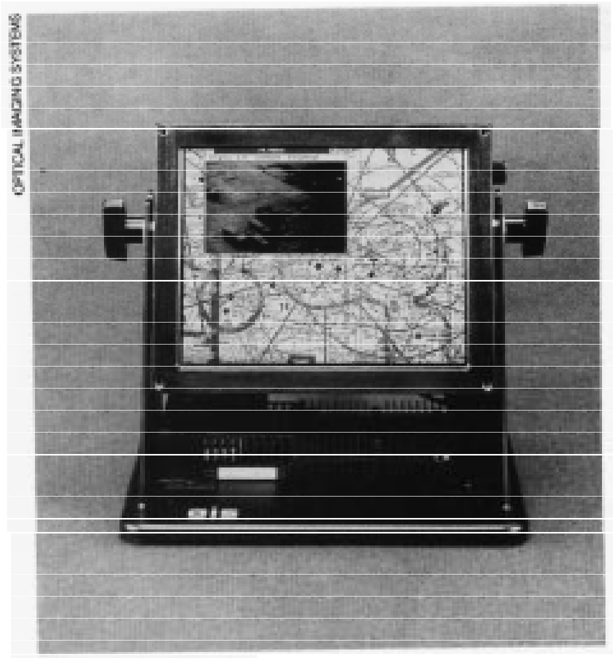
Large area workstation displays in aircraft, surface ships, submarines, and stationary positions (such as the Airborne Warning and Command Systems (AWACS) situation displays and Seawolf submarine sonar displays) are used for a wide range of logistical, tactical, and surveillance tasks.[51] There are approximately 15,000 large area displays, typically 20 inches or larger; these

[48] Al Rodriguez, product Manager, LCU Program, Fort Monmouth Army Base, NJ, personal communication, July 28, 1995.

[49] Ibid.; the first 3,000 units used monochrome PMLCDs; the remainder have used color AMLCDs.

[50] Ibid., and Johnson, op. cit., footnote 47.

[51] With 14 CRTs on each plane, the AWACS fleet alone constitutes approximately 500 displays; Robert Zwitch, System Engineer, Product Support Division, Warner Robins Air Logistics Center, Warner Robins AFB, GA, personal communication, June 28, 1995.



Military flat panel displays, such as this tactical map display must be designed or modified to withstand the adverse conditions imposed by military environments.

displays could use several different FPD technologies.[52] Replacing bulky CRTs with FPDs in these platforms will reduce weight, space, and costs. To date, several hundred large area FPDs have been fielded; these have mostly employed EL and plasma displays because of their light weight, compact design, scalable screen sizes, and high resolution, although projection displays are also used.

Very large area displays are used for presentations, briefings, and strategic map displays in command and control rooms like those at the North American Air Defense Command (NORAD). Direct view plasma panels and projection systems, using small FPDs such as Kopin's Smart Slide AMLCD or Texas Instrument's Digital Micromirror Device (DMD), are contending technologies for this group.

Cockpit Avionics

Military avionics demands higher performance and greater reliability than most other applications. Avionic displays present critical flight, targeting, and communications information to the pilot in harsh environments. As FPDs enable multiple functions to be performed by a single display, their performance becomes even more crucial to mission success and pilot survival. Even within avionics, however, the variety of platform types creates a range of operational environments and necessary display features. High performance, bubble canopy fighters require displays that: 1) can be read in very high ambient light; 2) are exposed to very high, direct sunlight heat (over 90 "C); and 3) can endure the shock, vibration, and stress of high altitudes, radical maneuvering, and combat. Transport planes and many helicopters operate in much less demanding environments; lower ambient light, altitudes, and temperature ranges relax conditions imposed on the display. Wider viewing angles for side-by-side pilots in such platforms are more important than in fighter aircraft.

The services have nearly 7,000 existing fixed wing aircraft and about 2,000 helicopters, each with multiple displays. In total, the potential market for retrofits exceeds 25,000 displays. Sinceretrofitting an aircraft is usually spread out over several years, this may result in an annual demand of a few thousand displays.[53] Given the high ambient light conditions in cockpits-and the requirement for video rate, full color, and high

[52] Randall E. Orkis et al., "A Full Color, High Resolution, 21" Common Large Area Display Set To Replace 19" CRTs in Several USAFC'1 Applications:' *1995 SPIE International Symposium on Aerospace/Defense Sensing and Dual Use Photonics Cockpit Displays II,* April 1995; Ted Klapka, Deputy Assistant Program Manager for Systems Engineering for P-3C,. Maritime Surveillance Aircraft Program Office, Arlington. VA, personal communication, July 13, 1995.

[53] David E. Mentley, "Flat Panel Displays for Military Airplanes:' *International Display Report,* Stanford Resources, Inc., San Jose, CA (distributed electronically by SEMI Newsletter Service), July 15, 1994; Darrel G. Hopper and Daniel D. Desjardins. "Requirments for AMLCDs in U.S. Military Applications," *SPIE International Symosium on Aerospace/Defense Sensing and Dual Use Photonics: Cockpit Displays II,* vol. 2462, April 1995, table 1.

TABLE 2-7: Examples of Active Matrix Liquid Crystal Displays in Current Military Programs

Military platform	Ruggedizer/ integrator	AMLCD source	Program status
Portable Systems			
Light computer unit (Army)	SAIC	Hitachi	approximately 13,000 delivered
Helmet mounted display (ARPA)	Hughes	Kopin	prototype
Vehicular/Shipboard			
Aegis fire control (Navy)	EDI	Sharp	approximately 25 delivered
Commander's tactical display (Bradley, Abrams)	Litton	Litton	prototypes
Driver vision enhancement (Bradley)	Interstate	Hosiden	operations testing
Avionics			
F-1 8 (Navy)	Kaiser	OIS	engineering/development
V-22 (Navy)	Kaiser	OIS	engineering/development
CH-46 (Marines)	Allied-Signal	OIS	operations testing
C-130H CGR (Air Force)	Grimes	Sharp	approximately 300 produced
UH-1 N (Navy)	Grimes	Sharp	operations testing
SH-60B (Navy)	Loral	DTI	n/a
F-1 6 CGR (Air Force)	EDI	Sharp	operations testing
RAH-66 (Army)	Litton	Litton	operations testing

KEY: AMLCD = active matrix liquid crystal display; ARPA = Advanced Research Projects Agency; CGR = Combined Air National Guard and Reserve; DTI = Display Technology, Inc. ; EDI = Electronic Designs, Inc.; OIS = Optical Imaging Systems, SAIC = Science Applications International Corp.

SOURCE, Office of Technology Assessment, 1995, based on personal communications with defense contractors and military program offices

resolution avionics displays—AMLCDs appear to be the best technology currently available to replace aging CRTs and electromechanical instruments.

■ Custom and Commercial AMLCDs: Choices and Convergence

There is much debate over the cost of custom AMLCDs and the suitability of commercial products for military applications, particularly in avionics. Custom FPDs offer reliable, high-quality performance in severe environments. However, commercial displays offer an affordable and often adequate solution for many programs, given sufficient ruggedization (see box 2-3). Although prices vary across applications, finished displays manufactured specifically for high performance avionics applications typically cost roughly three times as much as ruggedized commercial displays.[54] in many instances, custom AMLCDs offer superior performance: greater resolution, wider viewing angle, and greater environmental integrity. in others, commercial technology is still ahead—in areas such as grayscale and chip-on-glass interconnects—although custom units do conform to military requirements. in general, custom displays deliver greater performance and reliability than commercial units, but at a much higher price. This is the basic tradeoff faced by military programs. The choices made differ from program to program (see table 2-7).

Program choices reflect immediate needs, budgetary constraints, and operational missions and environments of their platform. Many older aircraft, especially those in the Air Force Reserve and Air National Guard (known as the Combined

[54] Johnson, op. cit., footnote 47; Randall E. Orkis, Principal Research Scientist, National Security Division, Battelle Memorial Institute, Columbus, OH, personal communication, May 5, 1995; Dan Doyle, Director of Display Products, Electronic Designs Inc., Westborough, MA, personal communications, May 22-24, 1995; and Klapka, op. cit., footnote 52.

BOX 2-4: Commercial Avionics and Automotive Displays

With niche markets in avionics and automotive displays emerging, commercial manufacturers are developing active matrix liquid crystal displays (AMLCDs) distinct from those used in consumer products such as notebooks and personal digital assistants (PDAs). in order to operate under conditions including high ambient light, vibration, shock, and extreme temperature variations, displays for avionics and automotive applications must perform at higher levels than commercial off-the-shelf versions. Several Japanese manufacturers are selling AMLCDs specifically designed for these applications Sharp produces a 4-inch automotive display that is being used in Delco products for police vehicles.[1] This AMLCD offers an operational temperature range from -30°C to +85 ‘C, a black matrix to improve sunlight readability, and vibration and shock resistance superior to its other displays.[2] FPD Co. of Europe is selling automotive displays to BMW.[3] Hyundai's investment in ImageQuest of California may allow it to offer AMLCDs in its automobiles.

Commercial avionics producers also use commercial AMLCDs. Hosiden supplied most of the displays to Honeywell for the Boeing 777 cockpit, and several firms, such as Toshiba, supplied the 3-inch AMLCDs for Traffic Collision Avoidance Systems required by the Federal Aviation Administration on all commercial jets.[4] Optical Imaging Systems has worked with several avionics companies, including Allied-Signal and Meggitt of Britain, to develop commercial avionics; its 5ATI (4- by 4-inch active area Air Transport Indicator) is used in several hundred Federal Express aircraft. Litton Systems of Canada is supplying multifunction AMLCDs for the Lockheed C-130J, an aircraft designed for commercial and military use [5]

SOURCE. Office of Technology Assessment, 1995.

[1] Steven Shields, Senior Scientist, Hughes Aircraft Co., Carlsbad, CA, personal communication, May 10, 1995, Sharp Electronics Exhibition, Society for Information Display (SID) Conference, Orlando, FL, May 22-24, 1995

[2] Sharp Electronics, ibid.; Randall E. Orkis, “An Improved Full Color F-16 A/B and F-16 C/D Multl-Function Display Using a Ruggedized COTS Active Matrix Color Liquid Crystal Display, ” *SPIE International Symposium on Aerospace/ Defense Sensing and Dual Use Photonics: Cockpit Displays II,* April 1995, p, 5.

[3] Robert Gray, Product Engineer, FPD Co., San Jose, CA, personal communication, June 5, 1995

[4] James Byrd, Technical Specialist, Cockpit Control Displays, Aeronautical Systems Center, Wright-Patterson AFB, OH, personal communication, June, 19, 1995; Curtis Casey, Vice President, Optical Imaging Systems, Northville, Ml, personal communication, July 14, 1995.

[5] Van Angelo, Manager, Business Development, Displays, Litton Systems Canada Ltd., Etobicoke, Ontario, personal communication, May 4, 1995.

Guard Reserve, or CGR), face reliability and maintainability problems; these programs need immediate (often stop-gap) replacements to keep their planes operational. Such programs also have small budgets for these retrofits. in reserve, defensive, and transport missions, aircraft are not as likely to face intense battle or flight conditions as are active duty and combat aircraft. High costs and the lack of certain features (such as gray levels sufficient for contrast in night vision conditions) dissuaded the CGR from using custom FPDs for its recent retrofit. Ruggedized automotive displays from Sharp Corp. (see box 2-4) are currently in operational testing and evaluation for the CGR.[55] At

[55] The Combined Guard Reserve has chosen a ruggedized commercial AMLCD for several F-16 and C- 130H air *wings; Dan Hamilton.* Ogden Air Logistics Center, Hill AFB, UT, personal communication, June 27, 1995, and Orkis, op. cit., footnote 54; Randall E. Orkis, “An Improved Full Color F-16 A/B and F-16 C/D Multi-Function Display Using a Ruggedized COTS Active Matrix Color Liquid Crystal Display, ” *SPIE International Symposium on Aerospace/Defense Sensing and Dual Use Photonics: Cockpit Displays II,* April 1995, p. 4.

least two other programs, the Navy's UH-1N and the P-3C, have also selected ruggedized commercial AMLCDs.[56] Rockwell-Collins, the only contractor to bid on the UH-1N using a custom domestic FPD, was informed that it lost the contract because of price.[57]

Other programs, such as the F-22, RAH-66, and F-18, involve both new and retrofitted aircraft whose operational environments impose adverse conditions. Aircraft with bubble canopies that fly high altitude combat missions place high demands on display integrity and performance. Programs with these requirements and—for new aircraft—larger development budgets have chosen custom displays. The foreign sales program of F-16s to Europe and Taiwan is currently undergoing a mid-life upgrade and is evaluating custom AMLCDs produced by Optical Imaging Systems (OIS); this evaluation may impact the choice for the Air Force's active duty F-16s and F-15s.[58]

Some high performance aircraft programs are also drawing on trends in the commercial avionics market. The CH-46 program took advantage of a commercial avionics display developed by OIS and Allied-Signal (see box 2-4); redesign costs were limited to driver attachment, bonding, and packaging.[59] As more standard commercial products emerge, military programs that make use of them will save thousands of dollars by avoiding nonrecurring engineering costs for unique designs and production.[60] The military increases these benefits by designing and adapting common display units and requirements for multiple platforms.[61]

AMLCD choices available to military programs have been facilitated by DOD initiatives and supporting legislation. The Perry Memo of June 29, 1994, and the Federal Acquisition Streamlining Act (FASA) of 1994 require program offices to justify the use of military specifications and afford them more freedom to draw from industry design, standards, and products when procuring display systems.[62] The Active Matrix Liquid Crystal Cockpit Display project,

[56] Bob Lehman, Naval Air Warfare Center, Warminster, PA, personal communication, June 27, 1995. The 6- by 8-inch display for the P-3 is one of many retrofits to that aircraft, several of which are using domestic custom displays; Klapka, op. cit., footnote 52.

[57] Michael McDonald, Marketing Manager, Rockwell-Collins Avionics and Communications, Cedar Rapids, IA, personal communication, July 14, 1995; recognizing that, for many programs, the primary constraint is on price, Rockwell-Collins has decided to switch to commercial FPDs for future bids.

[58] Tom Liberio, Avionics Engineer, F-15 Program Office, Avionics Systems Center, Wright-Patterson AFB, OH, personal communication, July 20, 1995; James Byrd, Technical Specialist, Cockpit Control Displays, Aeronautical Systems Center, Wright-Patterson AFB, OH, personal communication, June 19, 1995; Orkis, op. cit., footnote 54.

[59] Bob Mack, Naval Air Warfare Center, Warminster, PA, personal communication, June 26, 1995; Chris Mulford, Marketing Department, Commercial Avionics Systems, Allied-Signal Inc., Miami, FL, personal communication, July 12, 1995; Curtis Casey, Vice President, Optical Imaging Systems, Northville, MI, personal communication, July 14, 1995. The display may also be used in a P-3 retrofit; Klapka, op. cit., footnote 52.

[60] Dimensions of 6- by 8-inches, 4- by 4-inches, and 3- by 3-inches are becoming standard sizes for commercial avionics; McDonald, op. cit., footnote 57.

[61] The CGR hopes to use avionics developed for its F-16 retrofits for its A-10s and C-130s; Hamilton, op. cit., footnote 55. The Common Displays Program, part of the Air Combat Electronics Program Office, works jointly with program offices (currently with the AV-8 and F-18) to acquire common avionics for multiple platforms; Harlan Smith, Air Combat Electronics Program Office, Common Displays Program, Naval Air Warfare Center, Indianapolis, IN, personal communication, July 17, 1995. See also Darrel G. Hopper et al., "Draft Standard for Color Active Matrix Liquid Crystal Displays (AMLCDs) in U.S. Military Aircraft: Recommended Best Practices," WL-TR-93-1177, Avionics Directorate, Wright Laboratory, Air Force Materiel Command, Wright-Patterson AFB, OH, June 1994.

[62] William Perry, Secretary of Defense, *Memorandum for the Secretaries of the Military Departments, Subject: Specifications and Standards—A New Way of Doing Business*, June 29, 1994; Federal Acquisition Streamlining Act, Public Law 103-355 (Oct. 13, 1994); see also U.S. Congress, Office of Technology Assessment, *Assessing the Potential for Civil-Military Integration: Technologies, Processes, and Practices,* OTA-ISS-611 (Washington, DC: U.S. Government Printing Office, September 1994).

under Title III of the Defense Production Act (see chapter 3), provides funds to program offices to offset the cost of custom AMLCDs.

Another trend that blurs the distinction between custom and commercial displays is the emergence of niche markets for higher performance commercial AMLCDs. Increasingly, FPD manufacturers that sell to low-volume avionics markets, such as OIS and Litton Systems Canada, are working more closely with commercial manufacturers and markets to reduce the cost of custom units (see box 2-4). While some unit prices of custom displays in production volume have dropped nearly 50 percent, they are still at least twice the price of commercial displays.[63] Concomitantly, several high-volume producers are developing displays specifically for more rugged automotive and avionics environments. As custom producers look for commercial opportunities and solutions—and as commercial producers look to niche markets—the products, their performance, and their suitability for applications will converge.

The fact that programs have arrived at divergent solutions to meet their display requirements suggests that no FPD exhibits superiority. Very high performance platforms, such as the F-22 and the Space Shuttle, require very durable displays with redundant features and custom design; commercial displays may be adequate for reserve aircraft and transports. Yet the vast majority of military aircraft—fighter jets, bombers, and helicopters—lies between these two extremes. The distinction is not unique to aircraft. The Driver Vision Enhancement Program plans to introduce an inexpensive, infrared video display system for tanks and trucks. Contractors have been encouraged to keep costs low and use commercial products.[64] The Commander's Tactical Display for the Bradley Fighting Vehicle, however, is a high performance, multifunction display providing the user with crucial mission information; to date, this program has considered only a custom display.[65]

Custom manufacturers and some program offices are concerned that although ruggedized commercial FPDs have low up-front costs, their performance may not hold up, potentially imposing greater costs through shorter life cycles.[66] Others counter that, with ruggedization and maintenance, commercial displays provide excellent performance without the high cost of custom units.[67] Shorter life cycles, coupled with modular architecture, could allow for less expensive retrofits to introduce newer display features, which continue to be led by the commercial sector.[68]

Military programs are testing and evaluating both commercial and custom AMLCDs. At the same time, niche markets in avionics are pursued by both custom and commercial manufacturers. Over the next few years, DOD will be able to determine how well commercial displays hold up in military platforms, and custom manufacturers such as OIS, Litton, and ImageQuest will compete in commercial markets with high-quality displays.

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[63] OTA interviews with program officers revealed that during 1994, the unit price (in production volumes) of custom avionics FPDs from a domestic manufacturer was approximately $10,000 to $12,000, while a commercial off-the-shelf unit cost between $3,000 and $4,000; by mid-1995, some custom FPDs cost approximately $6,500, while commercial prices vary between $1,000 and $4,000 (prices do not include ruggedization and integration costs).

[64] Chuck Daz, DVE Program Representative, Texas Instruments, Dallas, TX, personal communication, July 28, 1995.

[65] Ibid.; Van Angelo, Manager, Business Development, Displays, Litton Systems Canada Ltd., Etobicoke, Ontario, personal communication, May 4, 1995.

[66] Casey, op. cit., footnote 59; James Moore, Naval Air Defense Center (Ret.), Wallington, PA, personal communication, July 5, 1995.

[67] Doyle, op. cit., footnote 54; Hamilton, op. cit., footnote 55; Orkis, op. cit., footnote 54.

[68] Orkis, "An Improved Full Color F-16 A/B and F-16 C/D Multi-Function Display Using a Ruggedized COTS Active Matrix Color Liquid Crystal Display," op. cit., footnote 55.