Appendix A: Flat Panel Display Technologies and Domestic Firms

A

Many technologies are used to create flat panel displays (FPDs). Some were developed years ago and fill small market niches; others have been brought to the stage of mass manufacturing and are now mature products; still others have yet to be commercialized, but promise superior performance and lower costs, compared with current technology. Numerous domestic firms are pursuing FPD technologies; most are small firms that focus on one or a few display approaches, but larger firms have also expressed interest. The distinguishing characteristic of the domestic FPD industry is the absence of high-volume manufacturing (see table A-1 for an overview of FPD technologies and domestic firms).

Chapter 3 outlined three potential strategies available to domestic FPD firms seeking a larger role in the global industry: 1) expand niche markets using established technologies; 2) catch up to leading-edge active matrix liquid crystal display (AMLCD) production; and 3) develop new leapfrog technologies. The following sections describe the technology choices associated with each approach, and place the activities of domestic firms into this framework.

ESTABLISHED TECHNOLOGIES: LCD, EL, PLASMA

Two of the oldest FPD technologies are liquid crystal displays (LCDs) and emissive displays. LCDs are the primary example of transmissive FPDs, which modulate an external light source. Emissive flat panel displays use materials that emit light when an electric field is applied, through phenomena that include gas discharge, phosphorescence, fluorescence, and semiconductor photoemission.

TABLE A-1: Flat Panel Display Technologies and Their Status in U.S. Firms

Technology	Leading U.S. firms	Production capacity	Strengths	Weaknesses	Foreign competition
'Passive matrix LCD: TN and STN	Standish Three-Five	2,3 million 2 to 3 million	low cost, simple manufacturing	response time, slow (TN) medium (STN); viewing angle limited; not scalable (TN); poor color	many firms in Japan, Taiwan, Korea, China, and Southeast Asia
Electroluminescent	Planar Norden Systems	120,000 5,000	bright; low power; simple manufacturing	no full color yet	Sharp
Gas plasma	Electro Plasma Plasmaco Photonics	6,000 15,000 5,000	bright, multicolor; scalable	high voltage; limited gray scale	Fujitsu, Matsushita/ NHK, Plasma Display Technical Forum, Thomson
Active matrix LCD: amorphous silicon TFT	OIS ImageQuest Xerox PARC	40,000 4,000 low quantities	excellent color, resolution	expensive; some yield problems; power hungry back-light, limited size	many firms in Japan; several in Korea and Taiwan
Active matrix LCD: other TFT and thin film diodes	Xerox PARC, David Sarnoff Research Center, Kopin	low quantities; (Kopin: 200,000 displays less than one inch)	high resolution	new technology; expensive substrate; difficult to scale up	Sony, Flat Panel Display Co., Litton Systems Canada
Field emission display	SI Diamond, FED, Coloray, Silicon Video, Raytheon, Micron Display, Tl, Motorola	experimental quantities only	may be scalable	new technology	PixTech Japanese, Korean firms
Digital micromirror device	Tl, Aura Systems	experimental quantities only	uses semiconductor processing	large-screen projection applications only	
Active addressed LCD	Motif, Positive Technologies	low quantities, external producers	high resolution; video rate; wide viewing angle	new technology; needs special drivers; not scalable	Optrex

KEY LCD = liquid crystal display, OIS = Optical Imaging Systems, PARC = Palo Alto Research Center, STN = supertwisted nematic, TFT = thin film transistor, Tl = Texas instruments, TN = twisted nematic.

SOURCES: U.S. Department of Defense, *Building U.S. Capabilities in Flat Panel Displays. Report of the Flat Panel Display Task Force,* October 1994, table 2-1 (using Department of Commerce data), company reports, Office of Technology Assessment interviews with companies,

Passive Matrix Liquid Crystal Displays

Liquid crystal (LC) materials are organic substances that flow like liquids, but possess the ordered physical properties of crystalline solids. The type of liquid crystal materials used most often in displays is the nematic LC, which consists of rod-like molecules. Weak intermolecular forces in the nematic LC tend to make the molecules align themselves parallel to each other along the long axis, similar to the schooling of fish. However, the molecules are not ordered in well-defined layers, and electromagnetic forces can rotate and translate the molecules relative to each other. The method by which LC materials modulate light is by altering the *polarization* of light as it passes through the LC layers.

An LC *cell* is fabricated by enclosing LC material between two glass plates, each with transparent metallic electrodes deposited on its inside surface. To control the orientation of the molecules, the electrode layers are coated with a polymer deposited in a hard varnish form, which is then brushed in a straight line. The rod-like molecules tend to align themselves parallel to the direction of brushing on the glass. Polarizer sheets (which pass only light that is polarized parallel to the lines on the sheet) are attached to the outside of each glass plate, with the polarization direction oriented parallel to the alignment direction.

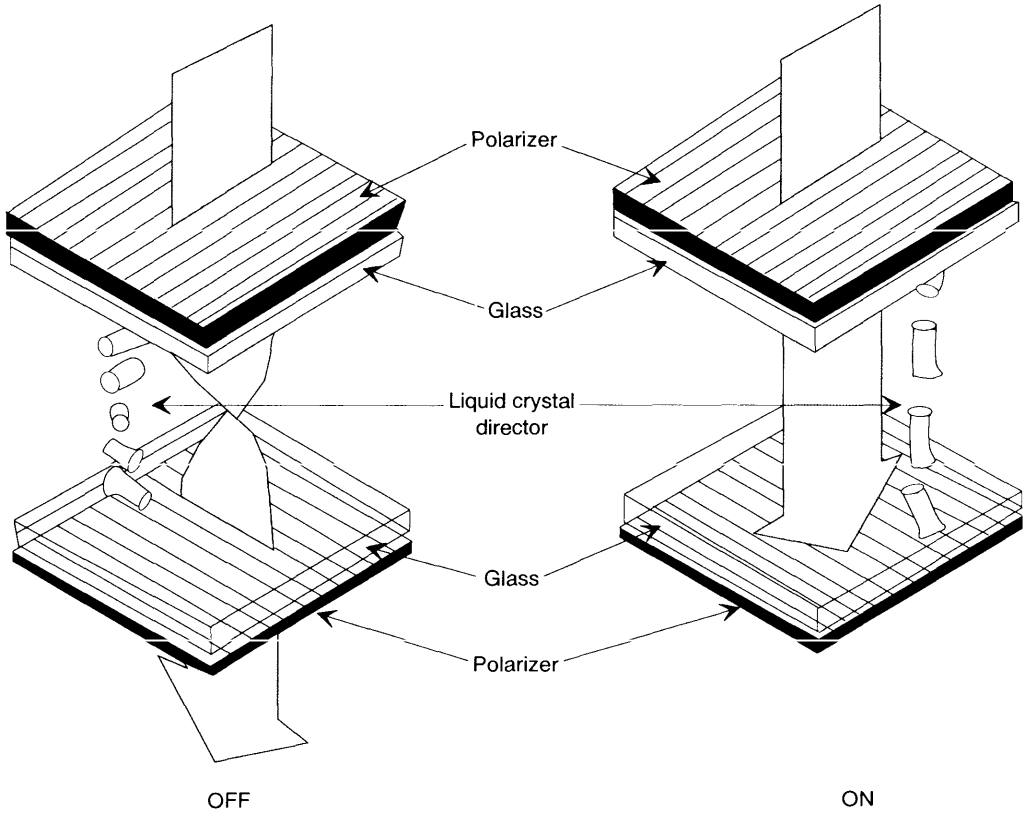
In the typical application of nematic LC materials, the *twisted nematic* (TN) liquid crystal display, each polarizer is oriented parallel to the direction of brushing on the adjacent glass plate, and the polarizer/glass plate pair is placed orthogonal (at a right angle) to the other pair. Since the alignment axes at the two LC-glass boundaries are now rotated 90 degrees relative to each other, the LC molecules align themselves in a spiral configuration within the cell, forming a helix (about an axis orthogonal to the cell faces) from one glass plate to the other. The LC molecules form layers parallel to the glass plates; each successive layer has a preferred direction rotated slightly from adjacent layers.

In the most common TN LCD configuration, called the *normally white* mode, the polarization of light entering the LC layer is twisted 90 degrees as it passes through the LC material, and is transmitted by the second polarizer (see figure A-1). Thus, with no applied field—the *off* state—the cell is light. When an electric field is applied across the cell, the LC molecules rotate parallel to the field, perpendicular to the faces of the LC cell. In this configuration—the *on* state—the polarization of the light is unaltered as it passes through the LC material. Because the polarization direction of the light as it exits the liquid crystal layer is oriented orthogonal to the second polarizer, the light is blocked, and the cell appears dark.

A TN LCD is made by creating a matrix of row and column electrodes; each intersection of a row and a column defines a *pixel*. Each pixel is selected to be on or off (light or dark) through application of an electrical signal to a given row, and an additive or subtractive signal to each of the columns along that row. This produces relatively large voltages across the *on* pixels and smaller voltages across the *off* pixels. The entire matrix is scanned on a row-by-row, or *multiplex*, fashion, which means that each pixel is *refreshed* once per scanning period, typically one sixtieth of a second (16.7 milliseconds). Since LC materials typically remain in the untwisted state for hundreds of milliseconds after being refreshed, there is not a noticeable decay in pixel brightness between scans. Multiplex addressing allows a matrix of x rows and y columns to be addressed with a total of x plus y electrodes, rather than the x times y that would be required with direct addressing, in which each pixel has an electrode dedicated to it alone. Thus addressing a color VGA (video graphics array) display through multiplexing requires just over 2,000 electrodes, compared with nearly 1,000,000 electrodes that would be required to directly address each pixel. Gray levels—intermediate pixel brightness between light and dark—can be created by turning the pixel on and off either within a pulse or from frame to frame.

The performance of the TN LCD is limited by an inherent tradeoff between contrast and the number of pixels, or resolution. Since both the electrode voltage and the rate at which the display

FIGURE A-1: Twisted Nematic Liquid Crystal Cell



SOURCE: Terry Scheffer and Jurgen Nehring, "Supertwisted Nematic (STN) LCDs " in 1994 *SID Intemational Symposium Seminar Lecture Notes* (Santa Ana, CA. Society for Information Display, 1994), vol. 1, seminar M-1, figure 1

pixels are updated (the *refresh* rate) are fixed, increasing the number of pixels decreases the difference between on and off signals and the amount of time that a voltage is applied to each pixel. Passive matrix schemes thus work well only for small numbers of rows in a TN LCD matrix, after which off pixels accumulate enough voltage to turn on partially. This effect, called *crosstalk,* increases with increasing numbers of rows in an array; for array sizes large enough to display television and computer images at an acceptable speed, the contrast between pixels becomes unacceptably low. This tradeoff between contrast and number of lines in the matrix has limited the use of TN LCDs to simple text and numeric displays in which the LC cells are arranged in fixed segments and are addressed directly, instead of through a matrix (for instance, watch and calculator displays).

The most effective method for enhancing the performance of a multiplexed LCD is to increase the amount of twist in the LC cell above the 90 degrees used in the TN LCD. When the twist angle within the LC layer is increased to 270 degrees, the transmission of the LC becomes more sensitive to differences in voltage. Higher contrast ratios can be obtained through this technique, and larger numbers of pixels can be addressed compared with the TN LCD. The introduction of such *supertwisted* nematic (STN) LC displays enabled the use of LCDs in computer displays.

Although they perform better than TN LCDs in large displays, STN LCDs still suffer from crosstalk and, thus, from the tradeoff between contrast and array size, or resolution. The scan time for a frame is too slow for full motion video display. Another limitation is that the large amount of twist results in separation of the color spectrum, called *birefringence*, producing nonuniform colors across the display. By using a second STN display with the opposite twist (double STN) or a layer of birefringent retardation film (film-compensated STN), true black and white displays can be fabricated. The latter approach is preferred because of its thin profile and light weight, and can be modified to display color through the placement of red, green, and blue color filters on one of the glass plates.

Despite these limitations, and the narrow viewing angle that limits most STN displays to single-person viewing, STN LCDs have found wide use as displays in portable computer screens and handheld electronic devices, and are the most common choice for passive matrix LCDs (PMLCDs). A recent innovation, called *dual-scan*, improves PMLCD performance by splitting the display horizontally and addressing each half independently. This reduces the effective number of rows in the display and, thus, the amount of crosstalk.

Standish Industries (Lake Mills, Wisconsin) is one of the most experienced American producers of PMLCDs. With $25 million in annual sales, Standish produces more than two million displays per year. These are mostly low-information-content displays for commercial and industrial applications, such as tractors, gas pumps, and office equipment. Standish also makes some customized military applications and collaborates with other firms on AMLCD development (see next section).

Three-Five Systems (Phoenix, Arizona), a manufacturer of passive matrix LCDs, had sales growth of 125 percent in 1994, to $85.5 million. Three-Five sells nearly five million LCDs per year (mostly manufactured in Asia) for use in handheld telecommunications, medical devices, and some military devices. Most of Three-Five's LCDs are low-information-content, alphanumeric displays, although a small portion are 1/4 VGA in resolution. In 1995, a new manufacturing facility opened in Phoenix. The facility, which has a capacity of over 280,000 square feet of LCDs per year, will produce more than 50 percent of Three-Five's LCDs; the remainder will continue to be purchased from Asian suppliers.

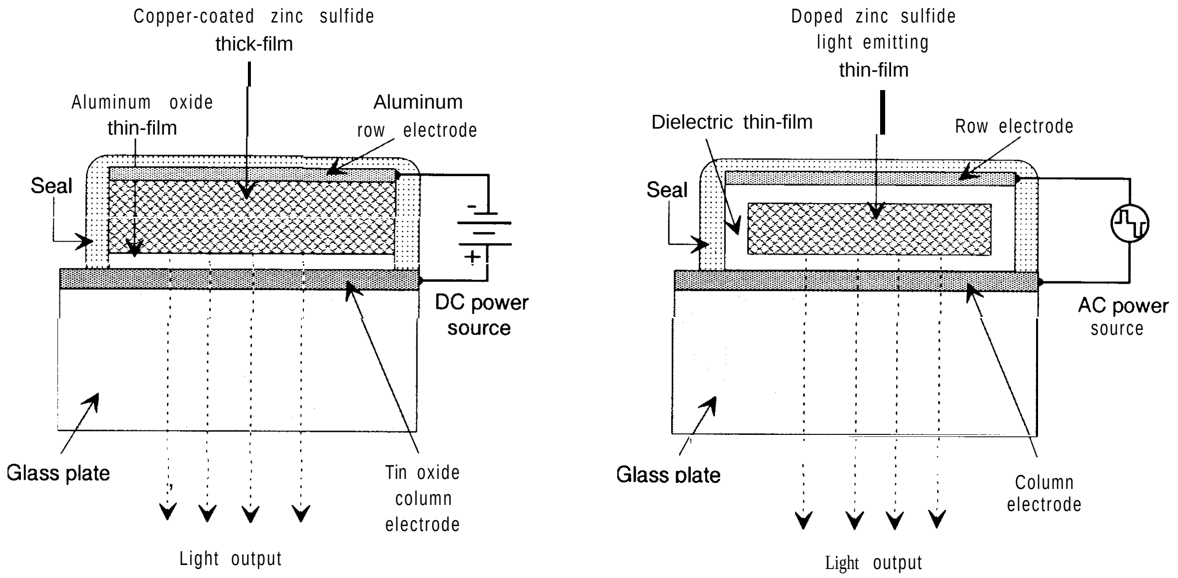
Electroluminescent Displays

Electroluminescence is the nonthermal emission of light generated by the application of an electric field to a material. Common arrangements use copper sulfide particles in a zinc sulfide lattice to serve as conductive or semiconductive inhomogeneities, ejecting electrons into a phosphor where they recombine to activate the emission process.

Electroluminescent displays (ELs) can be fabricated using a powder suspended in an insulator or, in the thin film EL (TFEL), using a thin (typically 0.5 microns) continuous film prepared by sputtering or vacuum evaporation (see figure A-2). The phosphor film is enclosed between two thin, transparent, insulating films, which are, in turn, sandwiched by transparent conductors. This conductor-insulator-phosphor-insulator-conductor stack acts as a capacitor; no light is emitted until the voltage reaches a threshold determined by the properties of the insulator and phosphor films. At the threshold voltage, electrons trapped at the insulator-phosphor interface are released into the phosphor film, activating luminescence. After passing through the phosphor, the electrons are retrapped at the second insulator-phosphor boundary; on reversal of polarity, the action is repeated and the electrons return to the original interface. Above the threshold voltage, the brightness increases steeply with applied voltage, until a saturation voltage is reached.

The phosphor film often used is manganese-doped zinc sulfide, which emits yellow light. Other phosphors that have been developed emit blue, green, red, and white light, with varying brightness. The development of phosphors with adequate brightness in these colors has enabled the fabrication of full-color TFEL displays. ELs can be constructed to operate at video rates, have good brightness characteristics, and are thin and reliable. Like plasma, EL displays are limited by high

FIGURE A-2: DC and AC Electroluminescent Displays



SOURCE Joseph A Castellano, *Handbook of Display Technology* (San Diego, CA: Academic Press, 1992), figures 61 and62

power requirements and difficulties controlling gray levels.

Planar (Beaverton, Oregon) is the world leader in EL manufacturing. Roughly half of Planar's annual production of 120,000 displays are manufactured in the United States, and half at its plant in Finland. Most of its $60 million in 1994 sales were in medical and industrial high-information-content displays. About 12 percent of sales were derived from military markets. Planar Advance, an avionics division recently acquired from Tektronix, is conducting cooperative R&D with Xerox on AMLCDs. Planar is leading a project funded by the Department of Defense's Advanced Research Projects Agency (ARPA) on thin film and active matrix EL technology for head-mounted displays.

Norden Systems (Norwalk, Connecticut), a subsidiary of Westinghouse, has produced EL displays since the early 1980s. Its plasma display plant in Connecticut was refitted in 1983 to manufacture EL displays. Norden earns most of its sales from customized, rugged, high performance military applications. The company plans to pursue more commercial and industrial markets, including transportation applications.

▮ Plasma Displays

Plasma devices operate on the principal of gas discharge. When subjected to an electric field, certain gases ionize, or break down into electrons and ions, causing the gas to glow. Plasma display fabrication is similar to LCD and EL manufacturing: glass plates with electrical conductors arranged orthogonal to each other encase the active material (typically a neon mixture) in a vacuum. The intersections of the row- and column- electrodes define the display pixels, effectively creating an array of miniature neon lamps. The characteristic color of plasma discharge is orange; in order to create color plasma displays, an ultraviolet-emitting gas is used to cause phosphorescent cell coatings—arrayed in sets of red, green, and blue—to glow.

The ability to fashion plasma display panels with high resolution (greater than 50 pixels per inch) in sizes greater than one meter in diameter has led some to consider using plasma technology for high definition television displays. However, plasma systems have some drawbacks, including high power requirements; high cost and electronics complexity; and generally thick display panels.

Plasma displays use either direct current (DC) or alternating current (AC) drive schemes. By supplying a voltage level equal to half of the threshold ionization voltage for the gas to both a row electrode and a column electrode, the gas in the pixel at the crossover point will discharge, emitting light. Since each pixel is emitting for only a fraction of the time, the display is somewhat dim. DC plasma displays can use batteries as power sources, which allows for portability, but the low efficiency of plasma systems requires large amounts of power, limiting such applications.

To enhance the brightness of plasma displays, a method of keeping the pixels glowing for a longer period of time is necessary. This can be accomplished by using AC as the energizing source. The fluctuations of the AC signal cause charge to be added to existing charge on the electrodes, triggering another discharge. The pixels fire every time the voltage reverses, which is a greater proportion of the time, and the effect is a brighter display.

Photonics Imaging, a subsidiary of Photonics Systems (Northwood, Ohio), manufactures both monochrome and color AC plasma displays. Its facility has a capacity of 5,000 displays per year, which are mostly used in military applications. Photonics recently demonstrated a prototype of a 21-inch, 1280- by 1024-pixel, full-color, video rate display.

Plasmaco (Highland, New York) manufactures high-information-content AC plasma displays. Its plant has a capacity of 15,000 monochrome displays per year. Plasmaco recently developed a 21-inch, 640- by 480-pixel color prototype. Although all of the work on monochrome units is completed internally, Plasmaco purchases some of its color display subassemblies, including glass substrates, from foreign producers. Plasmaco sells mostly to business and commercial markets, and some to the military.

Electro Plasma (Milbury, Ohio) has been producing AC plasma displays since the mid-1970s. Its facility produces between 5,000 and 7,000 displays per year, mostly for military and medical applications. Electro Plasma is working on a color plasma display.

Other manufacturers, such as Babcock, Cherry, and Dale Electronics, produce low-information-content plasma displays for industrial controls, medical devices, and arcade games. Annual display revenues for these firms is in the range of $10 million to $15 million.

Other Emissive Displays

Two other types of FPDs are commonly used in low-information-content applications, such as appliance indicators and simple text or numeric displays. Vacuum fluorescent displays (VFDs) operate on a principle similar to cathode ray tubes. A wire filament (cathode) is heated, creating thermal emission of electrons. The electrons accelerate past a grid structure and land on an anode, which is covered with a phosphor that emits light in response to the incident electrons. The VFD is in essence a flat cathode ray tube (CRT), but, unlike the CRT, is used only in small, simple displays. It is a mature and inexpensive technology, however, and is used widely in products such as videocassette recorders. The dominant producers are Japanese companies, including Futaba, NEC, and Ise.

Light emitting diodes (LEDs) are solid state devices typically fabricated from single crystal gallium-based semiconductors. Light emission is created at the junction of two materials having different concentrations of available electrons, causing flow across the junction. When electrons are combined with holes, light is emitted as a by-product. Hewlett Packard (Palo Alto, California) is a leading manufacturer of LEDs. Although LEDs are very inexpensive and reliable, the difficulty of constructing large arrays has limited display applications to simple indicators and gauges.

TABLE A-2: Comparison of Passive and Active Matrix Liquid Crystal Displays

Feature	Passive matrix	Active matrix
Liquid crystal mode	supertwisted nematic	twisted nematic
Contrast ratio	10-20:1	>100: 1
Viewing angle (degrees)[a]	horizontal: ±30 vertical: ±25	horizontal ±60 vertical +45, -30
Gray scale	16	256
Response time (milliseconds)	100-200	30-50
Multiplex ratio[b]	480	>1000
Size (Inches diagonal)	17	<14
Manufacturing	simple	complex
cost	moderate	high

NOTES

[a] Viewing angle is defined as the angle from the perpendicular to the display within which the image is visible at a contrast ratio greater than 5

[b] Multiplex ratio determines the limit of addressable Pixel rows for the display.

SOURCES: Thomas L. Credelle, “Passive Matrix Liquid Crystal Displays, in JTEC *Panel Report on Display Technologles in Japan,* Lawrence E Tannas and William E. Glenn (eds.) (Baltimore, MD: Loyola College in Maryland, June 1992), table 4 2: F C Luo, “Active Matrix LC Displays, ” in *Liquid Crystals: Applications and Uses,* Vol. 1, Birendra Bahadur (ed.) (Singapore: World Scientific, 1990), table 151

Several research groups have experimented with organic polymers that emit light (as opposed to LEDs, which are made from inorganic substances). Such materials could be used in the future to create low-cost, flexible displays.

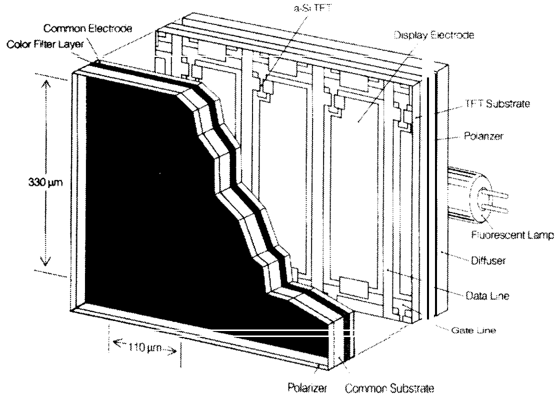
THE LEADING COMMERCIAL TECHNOLOGY: ACTIVE MATRIX LIQUID CRYSTAL DISPLAYS

The tradeoff between contrast and resolution in PMLCDs is a result of requiring the LC to handle both transmission modulation and addressing tasks. Active matrix addressing provides away of avoiding this tradeoff through the use of nonlinear switching elements at each pixel. Table A-2 compares passive and active matrix technologies in terms of several performance and production characteristics,

By addressing each pixel via a semiconductor switch and holding it in a steady state until addressed during the next scan, the active matrix allows for control over the transmission function of each pixel individually and independent of all other pixels. Since there is no crosstalk to limit the number of available pixels, AMLCD technology allows large, high-resolution displays. Since color displays require a threefold increase in the number of pixels, active matrix addressing has enabled high performance LCDs for computer and television screens.

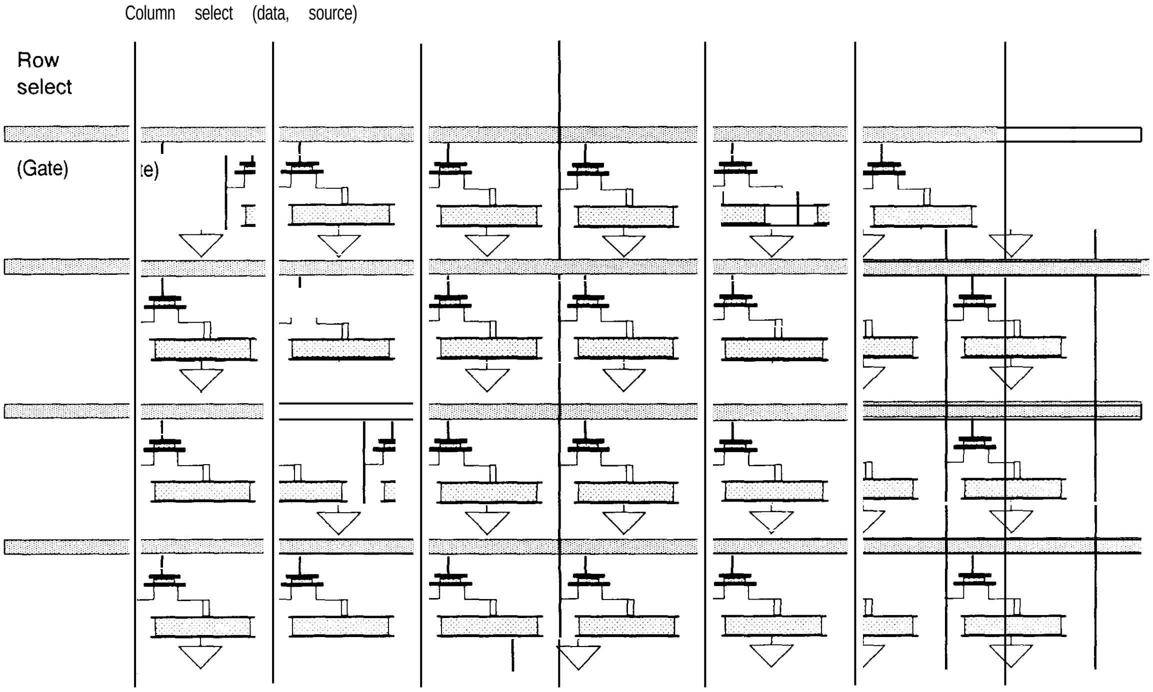
in an AMLCD (figure A-3), there is one switching element per pixel; this is typically a thin film transistor (TFT), but diodes have also been used in some AMLCDs. The TFTs in each row have one terminal connected to a row-addressing electrode (figure A-4). When a pulse is applied to a row

FIGURE A-3: Cross-Section of Active Matrix Liquid Crystal Display



SOURCE: Steven W Depp, Director, Subsystem Technologies and Applications Laboratory, Thomas J. Watson Research Center, IBM, 1995

FIGURE A-4: Thin Film Transistor Active Matrix Array



SOURCE. Arthur H Firester, "Active Matrix Technology," in *JTEC Pane/ Report on Display Technologies in Japan,* Lawrence E Tannas and William E Glenn (eds.) (Baltimore, MD Loyola College in Maryland, June 1992), figure 51.

electrode, each of the TFTs in the row is turned on, and the pixels in that row are ready to be addressed. The column electrodes, connected to a second terminal on the TFT, provide the appropriate voltage to set the gray level for each pixel. The third terminal of each TFT is connected to the active area of the LC cell. The LC material acts as a charge-storing capacitor, sandwiched between the TFT and a common electrode deposited on the other glass plate (a thin-film capacitor that stores charge is often added to each pixel). Each pixel can only be addressed when its TFT is on, thus eliminating pixel crosstalk; when the TFT is off, the charge is held in the LC capacitor until the next scan cycle, eliminating any effects due to relaxation of the LC material.

By allowing for many more pixels and using them in a redundant fashion, the AMLCD can produce better quality color than the PMLCD. Each pixel in a color display is made up of three or four subpixels, filtered in the additive primary colors (red, green, and blue; often with an additional white or redundant color pixel), which are combined to create other colors. Multiple gray levels, combined with additive color, produce a large color palette. The use of absorptive color filters makes color AMLCDs quite robust to use under conditions of bright ambient light (such as encountered in aircraft cockpits), since most of the ambient light is absorbed by the color filters and not reflected back to the observer (as with a cathode ray tube).

Color displays also increase the power required to produce a given screen brightness, as color filters typically absorb 75 percent of the incident light. Together with the polarizers, which absorb about 60 percent, and the nontransmitting portions of the LC layer, which absorb roughly 50 percent, the overall transmission of a color AMLCD is about 5 percent. The fluorescent lamps used in backlighting are efficient sources; even considering losses due to the diffusing plate used to smooth out the light from the narrow tubes, the backlight systems have efficiencies of 15 to 35 lumens per watt of electrical power. Accounting for the display transmission, the overall efficiencies for color AMLCDs are typically in the range of 1 to 2 lumens per watt. This is superior to the efficiency of cathode ray tubes, which are in the range of 0.5 to 3 lumens per watt.

Several types of nonlinear devices are used in AMLCDs to select and isolate individual cells for active matrix LCDs. The most common are amorphous silicon, polycrystalline silicon, and cadmium selenide TFTs. Due to several decades of solar cell research, amorphous silicon (a:Si) has the advantage of being the best understood material, and is used by most of the leading producers of AMLCDs.

Amorphous Silicon Thin Film Transistor AMLCDs

The predominant AMLCD TFT technology is the hydrogenated amorphous silicon thin film transistor (a:Si TFT). The a:Si TFT can be deposited at temperatures below 400 °C, allowing for the use of inexpensive glass substrates. While a:Si is well suited for the pixel elements, it has a low electron carrier mobility, limiting its use in fabricating row- and column-driver circuits. Column drivers must rapidly send data to all the pixels in a row during a row scan, and operate at frequencies greater than 10 megahertz in large arrays (row drivers are less demanding, operating in the kilohertz, because each row is held on while all the column data lines are pulsed). Unless the device features are 5 microns or less, a:Si cannot be used to fabricate display driver circuitry, which must be implemented in integrated circuits.

Optical Imaging Systems (OIS, Troy, Michigan) has built a medium-volume AMLCD manufacturing facility in Northville, Michigan, with a capacity of 40,000 displays per year. The majority of OIS's revenues comes from military programs. OIS produces customized FPDs for military systems and also sells displays to defense contractors, who then further modify the displays. OIS also produces some displays for commercial systems, such as avionics, and is developing standard displays for such applications. In a cooperative development agreement with Apple, OIS has agreed to provide limited quantities of 10.4-inch displays for portable computer replacements. OIS is considering construction of a high volume (as large as 1 million displays per year) plant to supply such a market.

AT&T High Resolution Technologies (Berkeley Heights, New Jersey), Standish Industries, and Xerox Palo Alto Research Center (Palo Alto, California) are working together in the American Display Manufacturing Partnership (ADMP), which received an ARPA grant to develop manufacturing processes for AMLCDs. In addition to Standish's LCD fabrication capability, Xerox's AMLCD development and AT&T's packaging capabilities will be used to develop product prototypes. Although the ADMP began in 1991, the three firms have made no decision yet to move forward with any joint manufacturing operations

ImageQuest Technologies (Fremont, California) is majority-owned (60 percent) by Hyundai, and works closely with Kent State's Liquid Crystal Institute. Its first product, a 6- by 8-inch AMLCD, is undergoing evaluation for a military display program. By 1997, ImageQuest expects its manufacturing facility to have a capacity of 4,000 displays per year.

Sharp Microelectronics Technologies (Camas, Washington) is a wholly owned subsidiary of Sharp Corp. of Japan. Over 300,000 AMLCDs and PMLCDs are assembled at the facility each year. Complete LC glass cells, backlights, and printed wiring boards are imported from Asia (mostly Japan). Sharp Microelectronics provides these standard LCDs for original equipment manufacturers of laptop computers in the United States.

Other AMLCDs

Polycrystalline silicon (p:Si) is similar to a:Si, but is deposited and annealed at a higher temperature (above 600 °C) to give it a quasi-crystalline structure and higher electron mobility. The high temperature required for this process has limited production device sizes to approximately five inches in diagonal on quartz or high-quality glass substrates. The high electron mobility of p:Si allows the fabrication of drivers with the speeds necessary for large arrays on the same substrate as the TFTs. As the driver electronics (which are external to the display in a:Si AMLCDs) comprise much of the cost in AMLCD production, this could reduce manufacturing costs. The p:Si TFT was used in the first commercial LCD display, a 2-inch pocket television offered by Seiko-Epson in 1984. Expansion of the technique to larger displays has been slow, however. At present, the p:Si process has a market niche in projection displays and videocamera viewfinders that use AMLCDs of a few inches or smaller. Xerox's Palo Alto Research Center and SRI's David Sarnoff Research Center (Princeton, New Jersey) are developing p:Si displays.

One of the first materials used in TFTs was cadmium selenide (CdSe), which outperforms a:Si in several ways. Because of difficulties in handling CdSe and the dominance of silicon materials, it has only been used in a limited number of custom displays. Litton Systems Canada (Etobicoke, Ontario) uses CdSe for AMLCDs in its cockpit avionics systems.

Single-crystal silicon (X:Si) processing involves fabricating circuitry on a conventional silicon substrate, removing the circuit, and bonding it onto a display substrate (glass or plastic) that is then used to assemble an AMLCD. Active matrix circuits using x:Si have higher electron mobility than p:Si, and higher optical transmission than other AMLCDs.

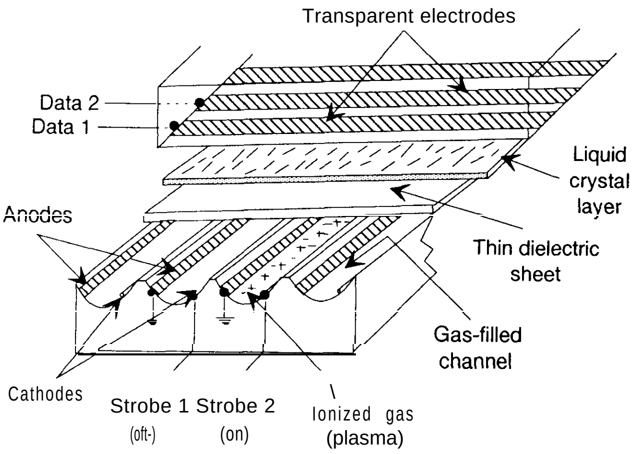
Kopin Corp. (Taunton, Massachusetts), with assistance from DOD, developed the x:Si technique for producing AMLCDs. To date, the company has been successful in using the process to build a high resolution display on small (1/2-inch or 1-inch) squares. Kopin's facility has a capacity of 200,000 displays per year, but has only produced small quantities to date. These small AMLCDs are used in helmet or head mounted displays (HMD) and in projection systems.

WAH III Technology (Novato, California) is also developing single-crystal silicon AMLCDs. Rather than peeling the etched circuitry from the silicon wafer, the WAH III process leaves the matrix and incorporates a reflective surface between the wafer and the active matrix. This small reflective AMLCD is currently used only for spatial light-modulating applications, but could develop into HMD and projection technology.

Future TFTs may be fabricated from organic polymers using simple printing techniques. Research groups have fabricated such devices and are developing production techniques. Unlike current TFTs, which use metals and semiconductors in a complex process, transistors made from organic polymers would be flexible. This would allow for plastic displays, which would be less costly to produce and lighter than glass displays.

Since transistors require connections between the row, column, and LC electrode at each pixel (figure A-4), TFT arrays must be fabricated by depositing the row- and column-electrodes and the TFTs on the same glass substrate. This has caused manufacturing problems because any deposition defects at the multiple crossover points lead to short circuits, creating bad individual pixels, rows of pixels, or columns of pixels. These problems have led to use of switching devices that only require connection to the column electrodes, thus separating the electrode sets onto separate substrates; semiconductor diodes have been used in this role, typically using metal-insulator-metal (MIM) fabrication techniques. The production process is simple, uses low-cost glass substrates, and can be done at temperatures below 300 °C. Diode arrays can be produced more reliably than TFT arrays because the row electrodes are fabricated on one glass substrate and the diodes and column electrodes are fabricated on the other, avoiding the possibility of crossed electrodes on either layer. MIM devices do suffer from limited nonlinearity and strong temperature sensitivity, resulting in gray scale nonuniformities. In terms of manufacturing cost and complexity, and device

FIGURE A-5: Plasma Addressed Liquid Crystal Display



SOURCE: Joseph A Castellano, *Handbook of Display Technology* (San Diego, CA Academic Press, 1992), figure 812

performance (contrast ratio and color display), MIM technology falls between the TFT AMLCD and passive matrix LCDs The leading firms in this area are Seiko-Epson of Japan and FPD Co. of Europe.

Another hybrid approach to AMLCDs involves using channels of ionized gas instead of rows of TFTs as the switching mechanism, combining gas plasma and LCD technologies. in plasma-addressed LC (PALC) displays, the channels are etched into the glass substrate, filled with an inert gas such as helium or neon, and sealed (figure A-5). The channels make up the rows of the array, and are fitted with two electrodes. When a voltage is applied to the electrodes, the gas in the channel becomes ionized and conducts current. The columns run perpendicular to the gas channel rows, and supply the analog pixel data. The LC is sandwiched between the row electrode array and the gas channels. Because the ionized gas is needed to complete the LC charging circuit, the column data voltages only have an effect on the pixels in a row for which a plasma channel is switched on. Thus, by charging the channel rows in sequence and sending data signals during the time the gas is switched on, the display is addressed row by row. Unlike AMLCDs that use TFTs, this technology is not limited in size by the semiconductor deposition process, and thus could potentially allow for low-cost production of large displays. PALC technology was developed by Tektronix (Beaverton, Oregon), which spun off a firm called Technical Visions, Inc. to pursue it; the new firm has developed a 16-inch prototype and signed a development agreement with Sony.

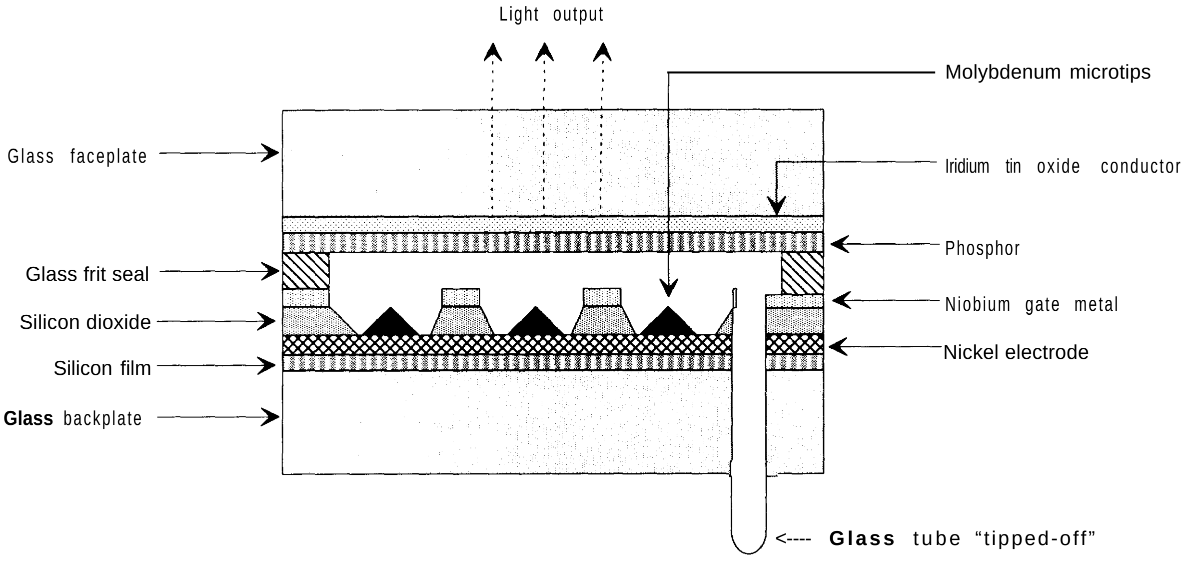
LEAPFROG TECHNOLOGIES: FED, DMD, and OTHER LCDs

Several FPD approaches currently underdevelopment could result in displays that produce higher quality images, require less power, and cost less to produce than commercially available FPDs. The two leading technologies are the field emission display and the digital micromirror device. While these technologies could leapfrog the AMLCD, they are closely related to established technologies such as the cathode ray tube and the semiconductor chip.

▮ Field Emission Displays

The field emission display (FED) is similar to the cathode ray tube in that it aims beams of electrons at phosphors deposited on the inside of a glass screen that emit light. Rather than one large electron gun, however, the FED uses arrays of *microemitters* in a flat display matrix. Each pixel consists of a large number of microemitters (often thousands), each about 1 micron in size and made of metal (such as molybdenum), silicon, or diamond, sealed in a vacuum (see figure A-6). Electrons are ejected from the microemitters under a high electrical field, and are accelerated onto the opposing phosphor. The redundancy of emitters for each pixel allows for failures of individual emitters without performance degradation, and the proximity of the microemitters to the phosphors provides sharp focusing. Production difficulties can arise from nonuniformities in the microemitters (resulting in brightness variation) and loss of vacuum (reducing microemitter performance). By replacing the microemitters with a thin diamond film, deposited by a silk-screening

FIGURE A-6: Field Emission Display Microemitter



SOURCE: J.A. Castellano, *Handbook of Display Technology* (San Diego, CA: Academic Press, 1992), figure 91

process, some of the fabrication difficulties can be mitigated.

PixTech of France was formed in 1992 to commercialize developments in FED technology at the Laboratoire d'Electronique, de Technologies et d'Instrumentation (LETI), a research laboratory of the French atomic energy agency that had built on work done at the American firm, SRI International. PixTech holds the rights to several FED approaches, and produced the first 6-inch diagonal FED. PixTech has formed alliances to accelerate the commercialization of FED; in addition to the Japanese firm Futaba, PixTech has signed bilateral cross-licensing agreements with Texas Instruments (TI; Dallas, Texas), Raytheon (Quincy, Massachusetts), and Motorola Corp. (Schaumberg, Illinois). Under the agreements, PixTech licenses FED technology developed at LETI, in return for the technology developed by each of the U.S. firms as it existed at the time of the agreement, and as it is subsequently developed over the period of the agreement, expected to be three years.

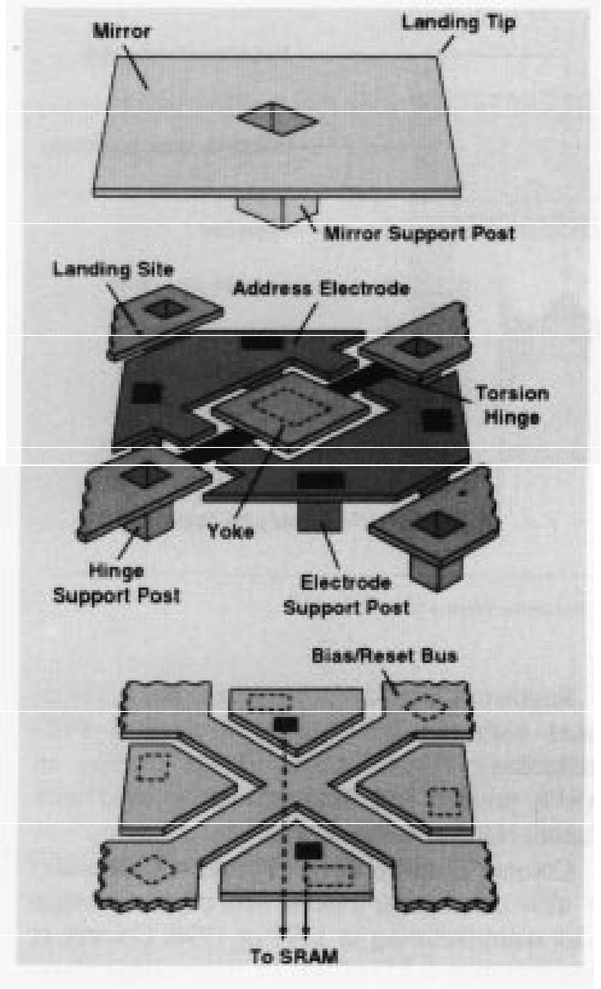
Raytheon, TI, and Motorola have also collaborated with the government to develop FED technology; Raytheon and TI are leading an ARPA project, and Motorola has worked with Sandia National Laboratories.

Coloray Display Corp. (Fremont, California) is also developing FEDs, and plans to begin pilot manufacturing in 1997 or 1998. Coloray is concentrating R&D efforts on low-voltage phosphors, glass sealing, electron optics, and lithography to improve manufacturing processes. Current R&D work is focusing on a process to construct larger FEDs.

FED Corp. (Hopewell Junction, New York) is developing a 7-inch, high-resolution FED for customized military applications. The company began building production facilities in 1994; the facility has a capacity of 10,000 plates per month. It has also worked with Zenith on large screen applications and with two other U.S. firms on a 10.5-inch prototype.

Micron Display Technology (Boise, Idaho) is a subsidiary of Micron Technologies, a leading U.S.

FIGURE A-7: Digital Micromirror Device, Individual Pixel



SOURCE: Gary Feather, Marketing Manager, Digital Imaging Venture Projects, Texas Instruments, 1995,

producer of memory chips. Micron has produced high-resolution, 1-inch FEDs for head-mounted displays, and has plans to produce FEDs of 10 inches and larger for portable computers.

SI Diamond Technology (Houston, Texas) has pioneered the use of thin diamond films instead of microemitters, with the assistance of several government grants. The company has developed a monochrome prototype, and initial production is planned for 1996. In work with the Phosphor Technology Center of Excellence, SI Diamond has devised and is patenting a means to extend the lifetime of low-voltage color phosphors to 25,000 hours. The company is also working with Russian partner, DiaGasCrown, on thin film diamond technology.

Silicon Video Corp. (Cupertino, California) is building prototypes and plans for full volume production in 1997. It is the leader of an ARPA-funded project to develop FED manufacturing technology. The company has strong corporate backing and the cooperation of Compaq and Hewlett Packard.

■ Reflective Displays

Reflective devices form images by controlling individual mirror elements in an array. Since an image cannot be viewed directly from a mirror array, reflective systems operate in projection mode, in conjunction with a high-intensity light and optical system. The image is projected onto a translucent screen from behind, or an opaque screen from the front, and allows large groups to view computer or television images.

The primary technique under investigation is called the digital micromirror device (DMD), developed by TI. The DMD is an electromechanical structure that is deposited using conventional semiconductor materials, processes, and fabrication lines in a standard integrated circuit chip package. The device contains an array of transistors over which an aluminum layer (etched into an array of square micromirrors) is deposited. Each mirror corresponds to a transistor, and is attached at two diagonally opposing corners to support pillars with torsion bars (figure A-7). Current passing through a transistor creates an electrostatic field, causing the mirror to tilt in response. In one position (the light state), the mirror reflects light from an illumination source to a projection system; in the other position (the dark state), the light is reflected away from the projection system. By flipping the mirror between light and dark states, continuous gray levels may be produced—the more often the mirror is in the light state, the brighter the corresponding pixel. By combing the reflection from three different colored light sources, a full-color display can be created. The response time of the device is very fast, and displays of 442,000 mirrors have been fabricated with scan rates of 100 per second. TI has not yet produced the display in commercial quantities, although it has entered into product development agreements with In Focus, Nview, Proxima, Rank Brimar, and Sony. Aura Systems (El Segundo, California) is developing a similar technology, but one that uses an analog, as opposed to digital, scheme.

Other LCD Materials and Addressing Schemes

LCDs made from ferroelectric liquid crystals (FLCs) exhibit switching speeds that are much faster than nematic LCDs, and have inherent memory: once set, the FLC remains in the same state, even after the electric field is removed. This memory property provides a method for getting around the tradeoff between contrast and resolution because, even in large arrays, individual cells remain at a constant state indefinitely. Since FLCs only have two states, however, they are not capable of displaying gray scales—and thus full color—which is a barrier to their use in computer and television displays. FLCs use a thin LC layer, producing wide viewing angles, because viewing angle increases with decreasing LC thickness. However, the tight assembly tolerances required by the thin layer make them hard to produce and sensitive to shock and vibration.

As yet, FLCs have not been produced in any large amounts, but Canon of Japan has developed several prototypes. In the United States, Displaytech and Boulder Nonlinear Systems (both of Boulder, Colorado) produce custom FLCs for research applications.

Another material in the research stage is the polymer-dispersed liquid crystal (PDLC)—also referred to as nematic curvilinear aligned phase (NCAP)—which scatters light at rest and transmits light under the presence of an electric field. The PDLC/NCAP display is made by encapsulating LC material in a transparent polymer, which is then sandwiched between layers of plastic coated with a transparent conducting film. The walls of the capsules do not alter the random alignment of the LC, causing scattering and an opaque appearance in the off state. The application of an electric field causes the LC molecules to be aligned with the field. The LC material then appears transparent and the pixel is on. Since they do not require the use of polarizers (which account for a large share of transmission loss in LCDs), PDLC displays have high transmittance. In addition, PDLC materials can be deposited on flexible plastic substrates. This could allow for high volume production runs on equipment used for handling polymer film. Due to difficulties in addressing arrays of pixels, however, PDLC cannot currently be multiplexed into high-information-content displays.

Raychem Corp. (Menlo Park, California) is currently developing PDLC displays, which are used with a reflective backing in a projection system. Kent Display Systems (Kent, Ohio) has developed a polymer-stabilized cholesteric-texture LCD; this LCD transmits as much as 90 percent of incident light, and is targeting low-information-content applications such as highway signs.

The response time of STN LCDs is just fast enough to follow cursor movement on a computer display, but too slow to display full motion video images. In an effort to improve video performance, several methods—referred to variously as active addressing, adaptive scanning, or multiline selection—have been developed to replace the common multiplex technique. These approaches use algorithms, hard-coded into electronic circuits off of the display, to drive the rows and columns in complex ways. Instead of sending a high voltage pulse down the rows, a set of predetermined signals (in the case of active addressing, based on Walsh functions) are applied to multiple rows simultaneously and a voltage, whose value depends on the state of the pixels in that column, is applied to the columns. The algorithms determine which rows need which signals, and calculate the proper column voltage within the timeframe allotted. In addition, the LCD has to be capable of switching at video rates; this means decreasing the cell thickness and using fast LC material. The active addressing approach allows for any number of lines (currently up to 255) to be addressed simultaneously.

In Focus Systems (Tualitin, Oregon) developed the active addressing technique, and is the world market leader in PMLCD projection systems. Although their products use both AMLCDs and PMLCDs, these displays are acquired externally, mostly imported, and incorporated into their systems. In Focus has invested this know-how in Motif (Wilsonville, Oregon). Motif is a $21-million joint venture between In Focus and Motorola to produce PMLCDs using the active addressing technique for use in commercial and communications applications. Initial plans to build a pilot manufacturing plant were scrapped in 1994, and the development of the application-specific integrated circuit (ASIC) prototype needed for active addressing was 18 months behind schedule. In March 1995, Motorola announced its intention to drop its share in the venture. Positive Technologies (San Diego, California) has developed the adaptive scanning technique for PMLCD performance enhancement. Although the technology has been provided to other producers of LCDs for business, transportation, and military applications, volumes have remained small. Multiline selection has been developed by Optrex of Japan, and is used in commercially available displays.