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# REVIEW

# LIQUID CRYSTAL DISPLAYS (LCDs)*

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**Abstract** – The current status of flat panel display (FPD) technologies is outlined, with emphasis on liquid crystal displays (LCDs). The principles of a number of LCDs are explained and compared with alternative technologies on the flat panel market. Recently announced LCDs, their structures, and their underlying technologies are summarized and compared.

## INTRODUCTION

During the 1970s and 1980s, all of the flat panel technologies were developing on a relatively broad front in the United States, Europe, and Japan. Among them, liquid crystal display (LCD) is a display device using the liquid crystal. The anisotropic electrical properties of liquid crystals that cause the director to respond to an applied electric field are the basis for most of the application of liquid crystals. Because liquid crystals have fairly low electrical conductivity, little power is consumed when an electric field is applied. Thus LCDs have become the dominant display devices where power consumption is an issue. However, because of cross-coupling (Tannas, 1985), LCD technology could not be applied to large arrays such as are required for television and computers. The contrast and viewing angle were degraded by a so-called sneak circuit between picture elements (pixels) turned on and those intended to be left off. This effect can be minimized with active matrix (AM) LCDs, in which diodes, field-effect transistors, or other nonlinear elements are constructed at each pixel. In the United States, the cost of such liquid crystal flat panel display (FPD) has been considered prohibitive; but several Japanese companies have perfected techniques to mass produce AMLCDs for high information content (HIC) displays, to add color, and to improve viewing angle performance. In parallel to the active matirx approach, a concerted effort was applied to passive matrix LCDs. A series of developments has rendered the super birefringent form of as well as color. This form of LCD, called compensated supertwist, possesses suffcient non-lineanity for manufacturing of high information content (HIC) computer displays, As yet, it does not possess sufficient speed or color for television video. The development of successful techniques to matrix address large arrays of LCDs during the 1980s is bearing fruit in the 1990s. The successful production of colored AMLCDs and low cost STN LCDs has changed the entire picture in the FPD industry. It appears that, out of all the FPD technologies, the LCD will dominate through the 1990s; it also appears that the order FPD technologies, such as EL, plasma, light-emitting diodes, and so forth, will be relegated to custom markets.

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## LCD TECHNOLOGY

LCD is derived at first from the developments of DS (Dynamic Scattering) mode[1] in 1968 and TN FEM (twist nematic field effect mode) in 1971. However, it was impossible to make a stable display at that time with those modes. The way out by TN[2] mode was introduced STN[3] (Supertwisted nematic) LCD mode. However, view angle, contrast, and switching speed and so on in this mode need to be developed. While, TFT[4] (thin film transistor) mode as a multiplex method, in which an active matrix addresses to a matrix one by one, has been studied. TFT LCD complemented with view angle of TN LCD; STN switching speed and contrast has been rapidly developed with the growth of semiconductor technology and became a main item of LCD confronting CRT. On the other hand, F (Ferroelectric) LCD[5] and AF (Antiferroelectric) LCD[6] by duty multiplex method has been also studied. Despite many efforts, a large flat panel display utilizing FLC seems to be still of no practical use. Recently reflectve color display using Cholesteric mode[7] and Guest-Host mode[8] been reported. However, in both cases, it was difficult to obtain bright high contrast full color images. PDLCD[9] (Polmer Dispersed liquid Crystal Display) is a new type of LCD, it consists of liquid crystal and polmer, but its novel mutilayer structure can reflect light at a specific wavelength and transmit light at other wavelengths. Furthermore, the reflection intensity can be controlled electrically. Because this device dosen't need polarizer or color filter, very little light is lost and it should provide bright color images.

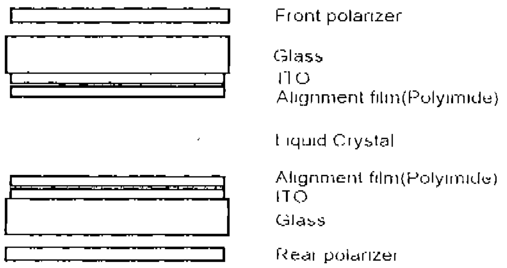


Figure 1. Twisted nematic liquid crystal display.

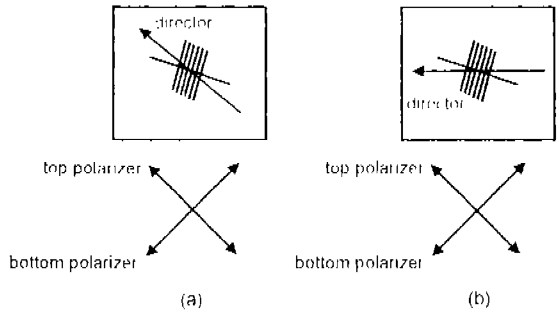


Figure 2. Top view of a surface stabilized ferroelectric liquid crystal display. The orientation of the smectic layers is shown in the center of each diagram. The angle between the director and normal to the smectic layers (the tilt angle) is 22.5°.

(a) The orientation of the director in the off-state.

(b) The orientation of the director in the on-state.

*Twisted nematic (TN) and supertwisted nematic (STN) LCDs*

The "workhorse" LCD display is the twisted nematic display. It has been production as a numeric display on wristwatches and calculators for many years, and os now becoming important for various machines (cash resisters, gasoline pumps, electronic test equipment, etc.). As shown in Fig. 1, the nematic liquid crystal used in this display is contained between two pieces of glass. A transparent electrode of indium-tin oxide is deposited on the side of each piece of glass in contact with the liquid crystal, followed by a polymer coating for orienting the liquid crystal. The polymer coating is rubbed in one direction, which in turn causes the liquid crystal director adjacent to the coating to orient parallel to the rubbing direction. What makes a twisted nematic LCD work is that the rubbing directions for the two inside glass surfaces are perpendicular to each other. Therefore, the director rotates by 90° in the liquid crystal occupying the 6-9 $\mu$m space between the two pieces of glass. Two polarizing films are added to the side of each piece of glass not in contact with the liquid crystal. These polarizing films on each piece of glass are oriented so that they allow light to pass if it is polarized parallel to the rubbing direction on the same piece of glass. Light striking the top polarizing film is polarized along the rubbing direction for the top piece of glass, and if the thickness and optical properties of the liquid crystal are chosen appropriately, the polarization of the light rotates with the director as it passes through liquid crystal. It therefore passes through the polarizing film on the bottom piece of the glass. In short, the liquid crystal display is transparent when there is no applied voltage. When a large enough voltage is applied to the electrodes, the director in the liquid crystal orients parallel to the electric field. This means that except for a thin boundary layer next to each piece of glass, the director is parallel to the light propagation direction. The light that is polarized by the top polarizing film remains polarized in this direction as it propagates along the director of the liquid crystal, so it is extinguished by the perpendicular polarizing film on the bottom piece of glass. Thus the LCD is opaque when a suitable voltage is applied. This type of LCD can be used in either a transmissive or reflective mode. In the transmissive mode, a light behind the display is blocked for those electrodes carrying an applied voltage. By shaping the electrodes into patterns for numbers and letters, black characters appear on a bright background. In the reflective mode, a reflecting layer is placed below the bottom polarizing film. For electrodes with no voltage, light that has passed through the LCD is reflected and passes through again. These areas appear to be silver colored to the viewer. Electrodes with an applied voltage appear black, since the ambient light striking the LCD is extinguished by the crossed polarizing films. A recent improvement to the contrast and viewing angle characteristics is to construct an LCD in which the director rotates 270° in going from one glass surface to the other, rather than 90°. This is called a supertwisted nematic display and it operates in essentially the same way as described above, except that the threshold voltage required to turn on the display element becomes very sharp and this allows better multiplexing. Some of these devices have rather unique properties such as bistability. In these devices the bistability is either intrinsic, meaning that the liquid crystal structure itself provides for the bistability, or extrinsic, meaning that the external environment (such as the surface structure) provides for the bistability.

*Vertically aligned nematic (VAN) LCDs*

The vertically aligned nematic (VAN), which is also known as the electrically controlled birefringence (ECB) effect, was first described in 1971 but was inferior to the twisted nematic effect. VAN-LCDs require homeotropic alignment of the liquid crystal molecules at the glass surface (long axis is perpendicular to the surface) and a negative dielectric anisotropy. Both conditions have been hade to achieve until recently. The principle of operation is based on a change in birefrihgence induced by tilting the molecules with applied field. A steep threshold characteristic can be achieved with careful control of the surface tilt angle and the cell spacing and by using liquid crystals with specific elasticconstants (high ratio of bend/splay elastic constants).

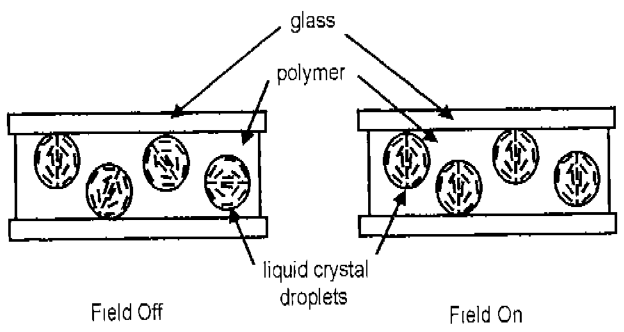


Figure 3. Polymer dispersed liquid crystal display.

*Surface stabilized ferroelectric (SSF)[10] LCDs*

These LCDs have been the subject of a great deal of research because of their relatively faster switching speeds. This LCD relies on the spontaneous polarization that is characteristic of chiral smectic C liquid crystals. If the helical structure of the chiral smectic C liquid crystal is suppressed, then a spontaneous polarization is present parallel to the smectic layers and perpendicular to the director. Such liquid crystals are therefore ferroelectric. Since the polarization direction is coupled to the director, the orientation of the polarization causes the director to reorient by twice the tilt angle in the smectic C phase. The helical structure can be suppressed by surface forces in a very thin cell, on the order of a micrometer thick, causing the director to lie parallel to the surface. The result is depicted in Fig. 2, which is a top view of the display. The smectic layers are perpendicular to the glass surfaces and for best results the angle between the director and the normal to the smectic layers is 22.5°. In this configuration, the spontaneous polarization is parallel to the applied electric field, into the page in Fig. 2(a) and out of the page in Fig. 2(b). Notice that the reversal of the direction of the electric field causes the director to rotate halfway around the normal to the smectic layers. If the top and bottom polarizers are oriented as shown in Fig. 2, then the light entering the LCD from above is polarized along the director in Fig. 2(a). Since this polarization direction is not changed at all in propagating through the liquid crystal, the light is extinguished by the bottom polarizer. The LCD appears dark. In Fig. 2(b), however, the light polarized by the top polarizer is at 45° to the director. If the thickness of the cell is matched to the birefringence of the liquid crystal in just the right way such that the cell acts as a half-wave plate, then the light emerging from the liquid crystal is polarized at 90° to its direction upon entering the LCD. Thus the light passes through the bottom polarizer and the LCD appears bright. Switching times in these surface stabilized ferroelectric LCDs can be on the order of microseconds.

*Polymer dispersed (PD) LCDs*

More recent development in LCD technology involves incorporating liquid crystal droplets in a solid polymer matrix (polymer dispersed liquid crystal or PDLC) or incorporating a polymer network in a bulk liquid crystal (polymer stabilized cholesteric texture or PSCT). Both of these schemes possess important advantages over conventional liquid crystals and are receiving considerable attention for commercial applications, because these display elements do not require polarizers. The PDLC display consists of a solid polymer containing droplets of nematic liquid crystalline material. The operating principle of this display is the refraction of light when it experiences a medium with a different refractive index. The higher contrast is obtained by the multiple scattering of light. When no electric field is applied to the PDLC film, the directors in the droplets point in all directions at random. This causes light passing through the film to encounter droplets with an index of refraction different from the polymer matrix and a large amount of scattering occurs. This makes the film cloudy white. However, when an electric field is applied, the directors of all the droplets align with the field so that light propagating through the PDLC is polarized perpendicular to the director in the droplets and the index of refraction of the polymer is chosen to minimize refraction. There is no mismatch in the indices, so no scattering occurs. This causes the film to appear clear. Fig. 3 Shows these two conditions for a PDLC display. Such films have already been commercialized as sunroof screens and window blinds. A PSCT[11] LCD is only slightly different from a display made entirely of a chiral nematic liquid crystal. If a chiral nematic material with a pitch in the visible is contained between two pieces of glass with the helical axis perpendicular to the glass, light with a wavelength in the vicinity of the pitch is rotated significantly and therefore passes through crossed polarizing films on the outer surfaces of the glass. A backlit display appears brightly colored. If an electric field is applied so that the director in the liquid crystal is everywhere perpendicular to the glass surfaces, no rotation of the light occurs so the display appears black due to the crossed polarizers. A small amount of crosslinking polymer is added to the chiral nematic material to overcome a problem of conventional chiral nematic displays, namely that it does not return to a defectless helical texture. The polymer network becomes the "memory" that allows the chiral nematic to return to its original zero-field texture each time. This also shortens the time for the display to switch when the electric field is removed (Yang and Doane, 1992).

*Multiplexing and active matrix addressing*

One of the technological problems that must be solved in any flat panel display device is how individual pixels are addressed. The magnitude of the problem becomes very apparent when one considers the number of pixels for a display on the order of several inches on a side with a resolution of 500 pixels per inch. Instead of making individual connections to each pixel, groups of electrodes are connected together and the voltages to these electrode groups are multiplexed. In order to work effectively, the cycle time for refreshing individual pixels must be short enough so that the state of the pixel is maintained and that the display does not appear too sluggish. In addition, the threshold behavior of the switching from one state to the other must be extremely sharp, since each pixel is exposed to voltages below threshold between the times it is refreshed. Sharp thresholds are often achieved by transferring the threshold behavior from the display elements to active integrated devices placed at each pixel. For example, the use of a thin film transistor (TFT) with a sharp threshold which in turn supplies the voltage to the pixel can allow the display to be multiplexed to a much higher degree. This scheme is known as active matrix addressing.

*a-Si TFT.*[12] The predominant AMLCD technology is the amorphous silicon TFT (a-Si TFT). One low mobility field effect transistor is used at each addressable dot where the low line is connected to the gate electrode for synchronization and the column line is connected to the source electrode and where the active area of the pixel is connected to the drain. Several forms of the TFT are used. Typically a storage capacitor is used at each pixel for improved performance. Most manufacturers believe that the a-Si TFT LCD has become the approach of choice for the AMLCD. It has good gray shades and color, fast response, and a wide viewing angle. Manufacturing machinery has been developed to make displays 15 inchs in diagonal. The latest accomplishment has been to significantly improve the viewing angle.

*p-Si TFT.*[13] The second high performing AMLCD uses poly silicon (p-Si) TFT LCDs. Poly silicon is very similar to a-Si except that it is deposited and annealed at a temperature above 600°C to give it quasi-crystalline structure and higher mobility. This technology is usually made on quartz substrate fabricated on metal-oxide semiconductor (MOS) line. Production machinery for large substrates has not yet been developed. The primary motivation for poly-Si TFTs is that have the mobility and speed for the peripheral row and column drivers and shift registers; therefore, they can be made at the same time and on the same substrate as the pixel TFTs. Additionally, the smaller substrate of an MOS line allows for smaller design rules for the circuits and higher resolution displays. These two features—higher mobility and higher resolution—make p-Si LCDs most suitable LC projector displays and LCD viewfinders for camcorders. Because of the process temperature, the p-Si LCD has not gone into large volume production for large displays (over five inches diagonal) in Japan. Seiko-Epson and others are developing a low-temperature (below 600°C) p-Si process. In the meantime, Seiko-Epson, Sony, and others continue to manufacture p-Si TFT LCDs for the higher performance, higher cost, smaller size applications.

*Metal-Insulator-Metal (MIM).*[14] A third AMLCD technology is metal-insulator-metal (MIM) diodes. At each pixel the MIM diodes are fabricated as a nonlinear device to prevent cross-coupling. This approach is less expensive than TFTs and gives better performance than the low-cost passive LCDs. Seiko-Epson and Toshiba have this LCD technology in production.

## CONCLUSIONS

Passive matrix LCDs dominate the FPD business today and will continue to dominate it, at least in unit sales, for next five years. The main thrust in active matrix technology is directed towards establishing cost-effective manufacturing of amorphous silicon AMLCDs. Both the STN LCDs and the a-Si AMLCDs have advanced to high levels of production. The lower cost STN LCD is used in word processors and computers, and the higher cost, higher performance a-Si AMLCD is used where video speeds and full color are needed. Between these two technologies in cost performance is the MIM technology, also in production and in the marketplace. Most global displays companies are committed to high-volume STN LCD and a-Si AMLCD production. In world, it is felt that STN LCDs (and derivatives using compensators and retardation films) and a-Si AMLCDs will be the dominant FPDs throughout the 1990s. They are expected to compete for market shares, with low cost on the one end and high performance on the other. The MIM approach will compete as a price /performance compromise between the lower cost STN LCD and the higher performing a-Si AMLCD. The other LCD approaches have not reached significant production comparable to STN, MIM, and a-Si AMLCDs. The ECB and FLC displays have not yet been put into production; however, two companies, Stanley and Canon, except production within a year.

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