

Liquid Crystal Displays

32.1	Introduction	32-1
32.2	Types of Liquid Crystal Materials.....	32-2
32.3	Physical Properties of Liquid Crystals.....	32-4
	Dielectric Anisotropy • Refractive Index Anisotropy • Elastic Constants • Electro-Optical Characteristics	
32.4	LCD Materials and Fabrication Processes	32-7
	Glass Substrate • Color Filters • Transparent Electrodes • Alignment Materials and Techniques • Cell Spacing and Sealing • LC Material Filling • External Components	
32.5	Liquid Crystal Display Modes.....	32-11
	Twisted Nematic Effect • STN Effect • Electrically Controlled Birefringence • Guest–Host Type • Phase-Change Type • Thermal Effects	
32.6	Display Addressing.....	32-15
	Passive Matrix Addressing • Active Matrix Addressing • Display Module Electronics	

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32.1 Introduction

Liquid crystals (LC) are an important class of materials with applications ranging from display devices, optoelectronic devices, sensors, and biological and structural materials. The focus of this chapter will be on LCs for display applications. In general, most substances have a single melting point where a solid possessing a positional and orientational order changes upon melting to an isotropic liquid that has neither positional nor orientational order. However, some materials when melted from the solid state change into a cloudy liquid with orientational order at one temperature, and upon further heating change into an isotropic liquid that has no order, as shown in [Figure 32.1](#). Thus, an LC is a mesophase existing between the melting temperature T_m , of a crystalline phase, and clearing point T_c , of the liquid phase; i.e., below T_m , the material has a crystalline phase, above T_c , it has a liquid (isotropic) phase, and between T_m and T_c , it has a liquid crystal phase. This type of LC in which the mesophase is defined by the temperature (between T_m and T_c) is called a *thermotropic* LC. When the mesophase is defined by a solvent concentration, it is called a *lyotropic* LC. Thermotropic LCs are used for display applications. The orientational order in LC materials results in important physical properties, such as birefringence, that make these materials useful for display devices. Because LCs have the attributes of low drive voltage, low power consumption, thin form factor (flat panel displays), light weight, full-color, gray scale with a wide dynamic range, full motion video, superior image quality, and high reliability, LC displays (LCDs) are the preferred approach for battery-powered (portable) applications ranging from wristwatch displays and handheld TVs to laptop computer displays. They are also replacing cathode ray tubes (CRTs) in select applications such as avionic displays because of their high brightness and readability in sunlight. LCs are also being used in projection display devices for head-mounted display (HMD) and for large-screen display applications. The following will discuss the various types of LC materials, their properties,

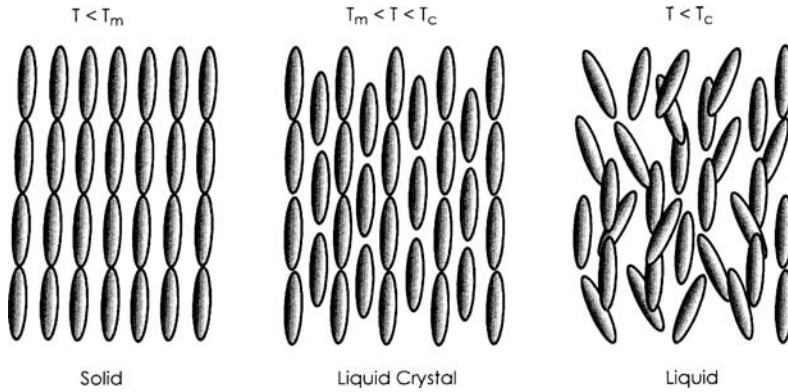


FIGURE 32.1 Illustration of a solid, an LC, and a liquid. A solid has an orientational as well as a positional order for the molecules. An LC has an orientational order only. A liquid phase is isotropic with neither positional nor orientational order.

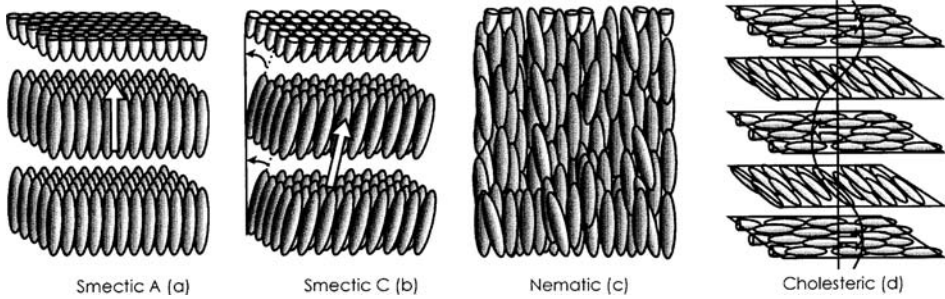


FIGURE 32.2 Molecular orientation in (a) smectic A, (b) smectic C, (c) nematic, and (d) cholesteric LC phases.

LCD materials and fabrication processes, various LCD modes, and display addressing methods. There are many good general references, for example, References 1 through 7, on LCs and LCDs. At the time of this writing, LCD technology is advancing very rapidly with respect to technology development for LCD products with improved viewing angles, improved image quality, lower power consumption, and larger display sizes. The purpose of this chapter, however, is to present the basic LCD principles and technologies, as opposed to reviewing the current state of the art.

32.2 Types of Liquid Crystal Materials

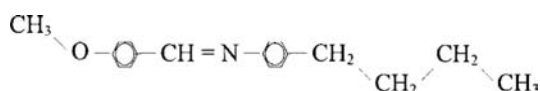
Most of the LC materials are organic compounds which consist of rod-shaped or disk-shaped molecules. For display applications, LC materials with rod-shaped molecules are the most commonly used. The LC materials are broadly classified into three types (phases) — smectic, nematic, and cholesteric — according to their molecular order, as shown in Figure 32.2. In a smectic liquid crystal, the rod-shaped molecules are arranged in layers with molecules parallel to each other. There are many different smectic phases, but smectic A and smectic C are the most common. In the smectic A LC, the molecular axis (director) is perpendicular to the layers as shown in Figure 32.2a, and in smectic C it is tilted at an angle from the layer normal as shown in Figure 32.2b. Also, in the nematic LC, the rod-shaped molecules are parallel to each other, but the individual molecules move relatively easily in the direction along their axis without a layer structure, as shown in Figure 32.2c. In the cholesteric LC, the molecules are arranged in a layered fashion as in smectic LC, but the molecular axis is in the plane of each layer as shown in Figure 32.2d. In addition, the cholesteric LC shows a helical structure in which the director \mathbf{n} changes from layer to layer. The same LC material may have different LC phases at different temperatures. For example, the

LC material may have a smectic C phase at a lower temperature, and as the temperature increases it may change to a smectic A phase and then to a nematic phase, before changing to an isotropic liquid phase at T_c .

The nematic LC is the basis for most widely used active matrix-addressed twisted nematic (TN) LCDs, and passive matrix-addressed supertwisted nematic (STN) LCDs. An example of a smectic C LC display is a passive matrix-addressed ferroelectric LCD [8]. An example of a cholesteric display is a passive matrix-addressed stabilized cholesteric texture (SCT) display with bistability [9]. A classic example of a nematic LC material is *p*-azoxyanisole (PAA) with a nematic phase in the range of 117 to 136°C.



In PAA, the two benzene rings are nearly coplanar and the rigid rod is about 20 Å long and 5 Å wide. Another historical example of a nematic LC is *N*-(*p*-methoxybenzylidene-*p*-butylaniline) (MBBA) with a nematic phase in the range of 22 to 47°C.



MBBA has a central group that connects the two ringlike cores firmly and serves to maintain the linearity of the entire LC molecule. The terminal groups and conjugated bonds in the core are largely responsible for the dielectric, optical, and other anisotropic properties of the material. Azoxy and Schiff's base compounds were among the materials used earliest in LCDs. Because of environmental stability problems, they were replaced by biphenyl materials. More recently, phenylcyclohexane, bicyclohexane, and estercyclohexane compounds are developed to satisfy the requirements of broad temperature operation and enhanced electro-optical characteristics. The LC materials used in current LCDs are highly developed mixtures of various compounds tailored to meet the requirements of environmental stability, wide operating temperature range, proper response to the applied electric field, high electrical resistivity for matrix addressing, and fast response time.

The degree of order in the LC is an important parameter, and is defined by the *order parameter*, S , given by

$$S = \frac{1}{2} \langle 3 \cos^2 \theta - 1 \rangle \quad (32.1)$$

where θ is the angle between the molecular axis and the predominant molecular orientation \mathbf{n} . The symbol $\langle \rangle$ represents averaging over the whole space. The predominant molecular orientation, which is known as the LC *director* \mathbf{n} is defined as the average alignment direction of the long molecular axis. For a perfect orientational order, i.e., when all the molecules align parallel to the director, as in a perfect crystal, $\theta = 0$ and thus $S = 1$. For no orientational order, i.e., for a completely random molecular orientation, as in an isotropic liquid, $S = 0$. In a typical nematic LC, S is in the range of 0.3 to 0.7, and in a typical smectic LC it is in the range of 0.7 to 0.8, with higher values at lower temperatures. Figure 32.3 shows the temperature dependence of S for the LC material PAA [10] as an example. The order parameter decreases rapidly to a value of around 0.3, close to the clearing point T_c , and becomes zero in the isotropic state. The exact dependence of S on temperature T depends on the type of molecules considered. However, the following analytical expression derived from theory has been shown to be useful [11]:

$$S = (1 - \gamma T/T_c)^\beta \quad (32.2)$$

where T_c corresponds to nematic–isotropic transition, γ is of the order of 0.98, and β is an exponent in the range of 0.13 to 0.18 depending on the material in question.

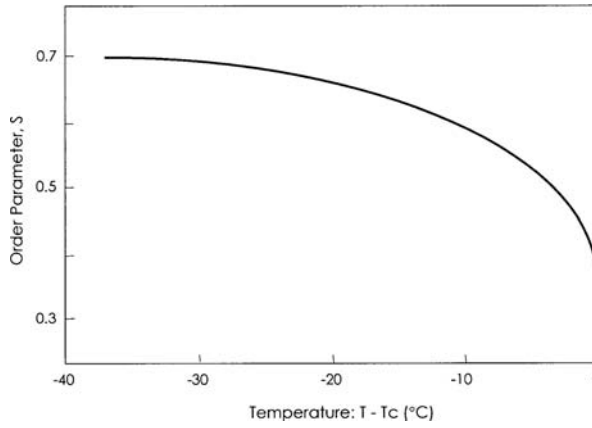


FIGURE 32.3 Temperature dependence of the order parameter S of the nematic LC P = azoxy anisole (PPA) [10]. S decreases with increasing temperature T , and rapidly approaches 0 near the clearing temperature, T_c .

32.3 Physical Properties of Liquid Crystals

Because of ordered structure with the molecules aligned with their long axis parallel to each other, LC molecules exhibit anisotropic properties. That is, various physical properties, such as dielectric constant ϵ , refractive index n , magnetic susceptibility χ , conductivity σ , and viscosity η , have different values in the direction parallel (\parallel) and perpendicular (\perp) to the molecular axis. The anisotropic physical properties, in conjunction with the ease of controlling the initial orientation (boundary condition) by surface alignment and the ease of reorienting the molecular axis by applying a voltage, is the basis for application of LCs for displays. The following will discuss the anisotropy of the dielectric constant and refractive index, elastic constants, and electro-optical characteristics which are important in the use of LCs for displays.

Dielectric Anisotropy

LC molecules exhibit dielectric anisotropy because of their permanent and induced dipoles. The dielectric anisotropy, $\Delta\epsilon$, is expressed as

$$\Delta\epsilon = \epsilon_{\parallel} - \epsilon_{\perp} \quad (32.3)$$

where ϵ_{\parallel} and ϵ_{\perp} are the dielectric constants measured parallel and perpendicular to the LC director. Materials that exhibit positive dielectric anisotropy ($\Delta\epsilon > 0$) are referred to as p -type materials and the materials that exhibit negative dielectric anisotropy ($\Delta\epsilon < 0$) are referred to as n -type materials. The p -type LC materials tend to align themselves with their molecular axis parallel to the applied electric field, whereas n -type materials align themselves with their molecular axis perpendicular to the applied field. Generally, the dielectric constant ϵ_{\parallel} decreases with increasing frequency [12] due to the relaxation phenomenon. However, ϵ_{\perp} is independent of frequency over a large range of frequencies. At the crossover frequency, f_c , where $\epsilon_{\parallel} = \epsilon_{\perp}$, the LC material becomes isotropic. Depending on the material, this frequency, f_c , falls in the range of 100 kHz to >1 MHz. The dielectric constants ϵ_{\parallel} and ϵ_{\perp} also change as a function of temperature [13], as shown in Figure 32.4 for the nematic LC cyanobiphenyl. The two dielectric constants rapidly converge as the temperature approaches T_c , where $\epsilon_{\parallel} = \epsilon_{\perp} = \epsilon_{\text{isotropic}}$.

Refractive Index Anisotropy

An LC is birefringent with anisotropic refractive indices. It has two principal refractive indices, n_o and n_e , as shown in Figure 32.5. For the ordinary refractive index n_o , the electric field vector of the light beam

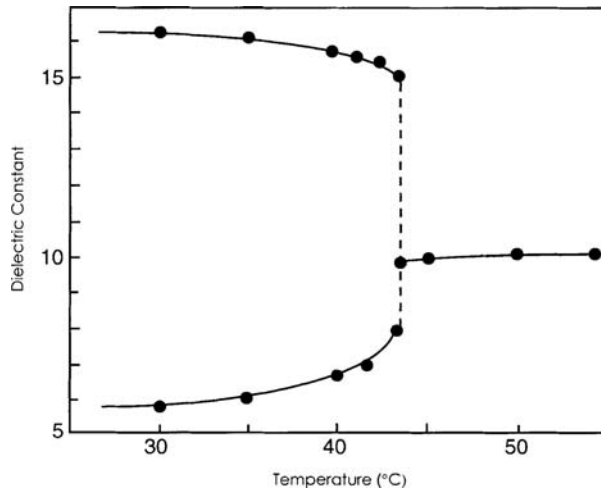


FIGURE 32.4 Temperature dependence of dielectric constant of the nematic LC cyanobiphenyl at a frequency of 100 KHz [13] exhibiting positive dielectric anisotropy ($\epsilon_{||} > \epsilon_{\perp}$). $\epsilon_{||}$ decreases with temperature, whereas ϵ_{\perp} increases with temperature until both are equal at the clearing temperature corresponding to the isotropic liquid.

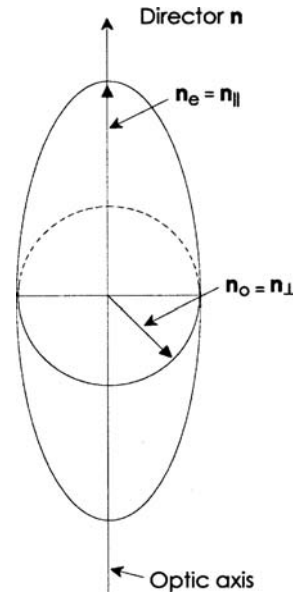


FIGURE 32.5 Refractive index anisotropy of uniaxial LC.

oscillates perpendicular to the optic axis, and for the extraordinary refractive index n_e , the electric field vector oscillates parallel to the optic axis. In the nematic and smectic LCs, the direction of the LC director \mathbf{n} is the optic axis of the uniaxial crystal and therefore the refractive indices for light rays with oscillations in the directions parallel and perpendicular to the director are $n_{||}$ and n_{\perp} , respectively, i.e., $n_o = n_{\perp}$, $n_e = n_{||}$, and the optical anisotropy or birefringence, Δn , is given by

$$\Delta n = n_{||} - n_{\perp} = n_e - n_o \quad (32.4)$$

Figure 32.6a and b show the temperature dependence [2] and wavelength dependence [2] of the refractive indices of typical LC materials. The dependence of refractive index on wavelength λ is generally expressed by the so-called Cauchy equation:

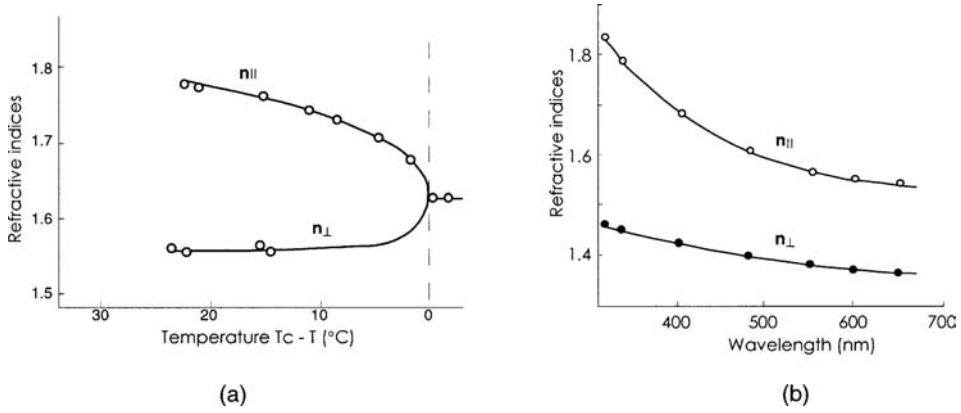


FIGURE 32.6 (a) Temperature dependence of the refractive indices $n_{||}$ and n_{\perp} for a nematic LC MBBA at $\lambda = 546$ nm; (b) wavelength dependence of refractive indices of the nematic LC 4-butoxyphenyl ester of 4'-hexyloxybenzoic acid at 80°C.

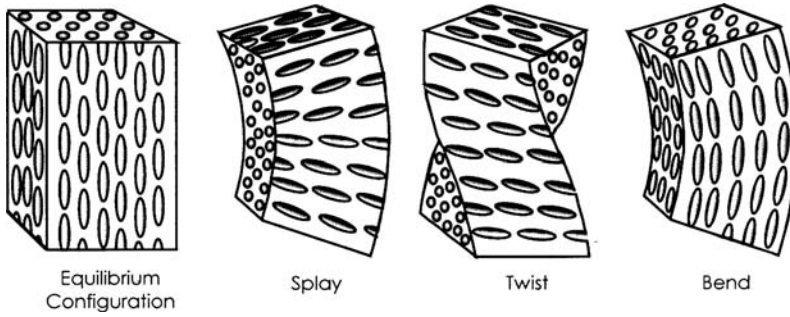


FIGURE 32.7 Deformation of nematic LC molecules from equilibrium configuration is shown in (a). Three types of deformations — (b) splay, (c) twist, and (d) bend can describe all possible types of deformations.

$$n_{o,e} = n_{\infty} + \alpha_{o,e} / \lambda^2 \quad (32.5)$$

where n_{∞} is the refractive index extrapolated to infinite wavelength and α is a material-specific coefficient.

Elastic Constants

In uniaxial LCs, the preferred or equilibrium orientation of the LC molecule is given by the director \mathbf{n} , which may be imposed by the surface treatments at the boundary conditions or by an external field. When the LC is perturbed from an equilibrium condition by application or removal of an external field, the elastic and electrical forces determine the static deformation pattern of the LC. The transition of the director from one direction to the other induces curvature strain in the medium. Frank [14] showed that an arbitrary deformation state can be envisaged as the combination of three basic operations; *Splay*, *Twist*, and *Bend*, denoted by the elastic constants K_{11} , K_{22} , and K_{33} following the notation of the Oseen–Frank theory. Figure 32.7 illustrates the *Splay*, *Twist*, and *Bend* deformations. The elastic part of the internal free energy, F , of a perturbed liquid crystal is given by the equation:

$$F = \frac{1}{2} \left[K_{11} (\nabla \cdot \mathbf{n})^2 + K_{22} (\mathbf{n} \cdot \nabla \times \mathbf{n})^2 + K_{33} (\mathbf{n} \times \nabla \times \mathbf{n})^2 \right] \quad (32.6)$$

The free energy density is thus a quadratic function of the curvature strains with the elastic constants appearing as constants of proportionality. The elastic constants K_{11} , K_{22} , and K_{33} are temperature dependent, and decrease with increase in temperature. The magnitudes of the elastic constants, K_{ii} , can be approximated [15] by

$$K_{ii} \propto S^2 \quad (32.7)$$

Electro-Optical Characteristics

When an electric field is applied to an LC with an initial molecular (director) orientation, it will change to a new molecular orientation due to the dielectric anisotropy ($\Delta\epsilon = \epsilon_{\parallel} - \epsilon_{\perp}$) of the LC. This change in molecular orientation is accompanied by a change in the optical transmission/reflection characteristics of the LC which forms the basis for LCDs. This phenomenon of an electrically driven optical modulation is known as the electro-optic effect of the LC. When an electric field E is applied to an LC, it produces an electric energy, f_e , given by

$$f_e = -\frac{1}{2}\epsilon_{\perp}E^2 - \frac{1}{2}\Delta\epsilon(n \cdot E)^2 \quad (32.8)$$

The initial molecular orientation (boundary condition achieved by surface alignment) of the LC molecules (director \mathbf{n}) is either parallel (for $\Delta\epsilon > 0$) or perpendicular (for $\Delta\epsilon < 0$) to the plane of the two parallel electrodes of the display. When a field is applied across the parallel electrodes with the LC material in between, the director \mathbf{n} orients parallel to the electric field E in +ve $\Delta\epsilon$ materials, and it orients perpendicular to the field in -ve $\Delta\epsilon$ materials. The total free energy, F , of the LC when the initial undeformed molecular orientation undergoes deformation due to the applied field is given by the sum of the electric energy f_e and the elastic energy. This transition from an undeformed state, known as *Freedericksz transition*, occurs as the field is increased to a critical field E_c . The Freedericksz transition is simply a transition from a uniform director configuration to a deformed director configuration; i.e., at any point in the LC, the order of the molecules relative to one another remains the same. The threshold electric field, E_c , is calculated by a free energy minimization technique [3], and it is given by

$$E_c = (\pi/d)(K_{ii}/|\Delta\epsilon|)^{1/2} \quad (32.9)$$

Thus the threshold voltage V_{th} of the LC electro-optic effect is given by

$$V_{th} = E_c d = \pi(K_{ii}/|\Delta\epsilon|)^{1/2} \quad (32.10)$$

In Equations 32.9 and 32.10, d is the thickness of the LC and k_{ii} is the appropriate elastic constant. When the field is perpendicular to the initially homogeneous orientation of the director, $K_{ii} = K_{11}$ or K_{22} . When the field is parallel to the initially homogeneous orientation, $K_{ii} = K_{33}$. In the case of a twisted orientation, $K_{ii} = K_{11} + (K_{33} - 2K_{22})/4$.

32.4 LCD Materials and Fabrication Processes

There are several types of LCDs utilizing different LC materials and LCD modes which are discussed in the next section. However, the general display assembly processes and materials are very similar for all these LCD modes. Figure 32.8a and b show the plan and cross-sectional view of a passive matrix-addressed LCD. The display fabrication can be broadly divided into three parts: (1) lower and upper glass fabrication processes, (2) cell assembly processes, and (3) polarizer and driver attachment and module assembly

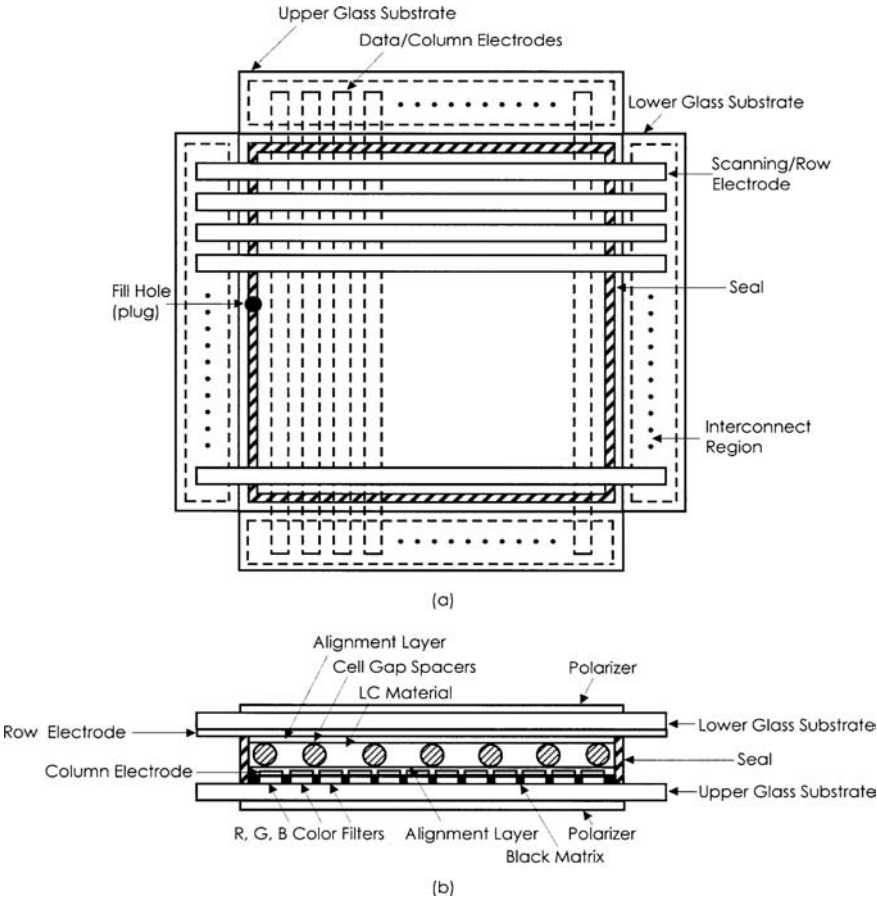


FIGURE 32.8 Plan (a) and cross-sectional view (b) of a passive matrix-addressed LCD.

processes as illustrated in Figure 32.9. The following will describe the various display materials and the assembly processes.

Glass Substrate

The quality of the glass substrate is important with regard to its chemical compatibility with the LC materials, surface flatness, defects, and dimensional stability under processing temperatures associated with various display fabrication steps. With a typical LCD cell gap in the range of 5 to 10 μm , the importance of the glass flatness and surface quality is clear. Glass substrate defects such as voids, scratches, streaks, and attached particles can cause electrode defects and hinder uniform LC cell spacing. Therefore, depending on the type of display, glass substrates are sometimes polished to achieve the required surface quality. Typical display glass materials include borosilicate (e.g., Corning 7059) and aluminosilicate glasses (e.g., Corning 1737), with a thickness of 0.7 or 1.1 mm.

Color Filters

In full-color LCDs, color most often is generated by use of red, green, and blue (R, G, B) color filters fabricated at each pixel, as shown in Figure 32.8b, using a white backlight system. The color filter requirements include proper spectral transmission characteristics and chemical, thermal, and dimensional stability. The display color gamut is a function of the spectral characteristics of the backlight used

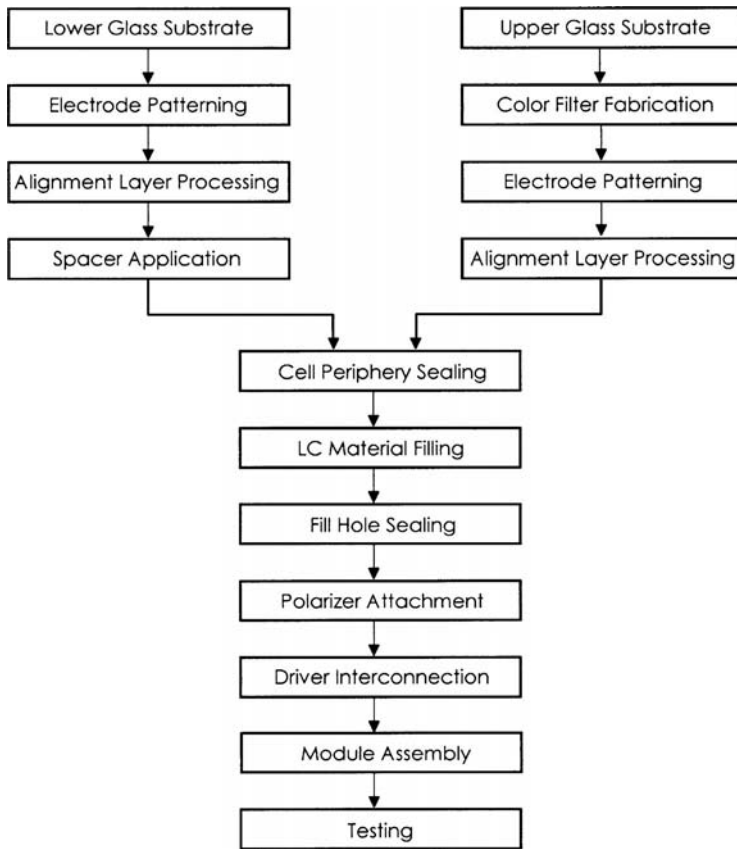


FIGURE 32.9 LCD assembly flowchart.

and the color filter transmission characteristics. By a suitable choice of these parameters, an LCD can achieve a color gamut comparable to that of a high-quality CRT. However, trade-offs are sometimes made between color purity and transmission (brightness) characteristics of the LCD. Typical color filter thickness is about $2\text{ }\mu\text{m}$. Color filter materials include dye and pigment dispersed polyimides and photoresists. The color filter materials are applied on the display glass by various processes, such as spin coating, printing, electrodeposition, and photolithography. First, color filter material of the first color is applied and photolithographically patterned. Then, the color filter material for the second color is processed, and then the third. A black matrix material is also applied and patterned between the color filters to block the light transmission from the interpixel regions. In some cases, a passivation layer such as low-temperature SiO_2 dielectric is deposited on the color filters to act as a barrier for impurities and to achieve a smooth surface for the subsequent transparent electrode deposition.

Transparent Electrodes

Most often, indium tin oxide (ITO) with a typical concentration of 90% In_2O_3 and 10% SnO_2 is used as the transparent conducting electrode material. The typical transmission of ITO is about 90%. It is generally deposited by e-beam evaporation or sputtering in an oxygen-containing atmosphere. The film thickness is typically 50 to 300 nm depending on the required sheet resistance and transmission. Typical resistivity is in the range of $2 \times 10^{-4}\text{ }\Omega \cdot \text{cm}$. Light transmission through ITO is not linearly proportional to the film thickness because of light interference.

Alignment Materials and Techniques

After the transparent electrodes are patterned, an LC alignment coating is applied. Depending on the display mode of interest, either a homogeneous (parallel), tilted, or a homeotropic (vertical) alignment is achieved using an appropriate alignment material and process. The most commonly used TN LCD requires a tilted alignment to eliminate reverse tilt disclinations. Inorganic films such as an obliquely evaporated SiO₂, as well as organic materials such as polyimide, can be used as alignment materials. Polyimide is most commonly used as an alignment layer. It is spin-coated or printed to achieve a layer thickness of about 50 nm, and cured around 150 to 200°C. It is then buffed (rubbed) using a roller covered with cotton or a synthetic fabric. For TN LCD, the alignment process is selected to achieve a pretilt angle of around 2 to 5°.

Cell Spacing and Sealing

The cell assembly process starts after the alignment layer treatment of the two substrates by rubbing. To control the LC cell spacing (thickness) accurately, spacing materials are applied in the active area of the display as well as in the peripheral seal area, where the two glass substrates are sealed. Typical spacing materials include glass or plastic fibers (cylinders) or spheres (balls), with a tightly controlled size (diameter) distribution. A sealing adhesive material such as an epoxy is then applied at the seal area with an opening (fill hole) left for LC material injection after the sealing process. The seal is typically 1 to 3 mm wide and is a few millimeters from the active display area. The requirement for the seal material is that it must not chemically react with (contaminate) the LC material and must be a barrier against moisture and contamination from outside. After the spacers and seal materials are applied on the first (active) substrate, it is precisely aligned to the second (color filter) substrate, and the seal is cured either by heating it to a higher temperature, typically 100 to 150°C, or by ultraviolet exposure depending on the type of epoxy seal material used.

LC Material Filling

After the empty cell is fabricated, it is filled with the LC material. Because the cell thickness (spacing) is small (~5 to 10 μm), it is filled using special techniques. The most popular filling method is by evacuating the cell in a vacuum chamber, dipping the fill hole into a vessel containing the LC material, and increasing the pressure in the chamber. As the chamber pressure is raised, the cell gets filled by capillary action. After the cell is completely filled, the fill hole is capped by using an epoxy adhesive that is chemically compatible with the LC material.

External Components

The external components of an LCD include polarizers, reflectors, display drivers, and a backlight assembly. A reflective LCD uses a reflector at the back of the display, works by modulating the ambient light, and does not require backlighting. In the most commonly used transmissive mode TN LCDs, a polarizer is attached on the front as well as back surfaces of the LCD after the cell assembly is complete. Also, in the most commonly used normally white mode TN LCD, the polarizers are attached with their polarization axis crossed and along the rubbing directions of the alignment layers. The polarizer is a three-layer composite film with a stretched iodine doped polyvinyl alcohol (PVA) polarizing film in the center, and two outer films of triacetyl cellulose (TAC) for protecting the PVA film from the ambient (moisture, temperature, and harsh environment) conditions. A typical transmission range of a polarizer is 41 to 45%, with a polarization efficiency in the range of 99.9 to 99.99%.

The display row and column IC drivers are attached to the row and column bond pads of the display either by TAB (tape-automated bonding) using an ACA (anisotropic conductive adhesive), or chip on glass (COG) approaches. For backlighting transmissive LCDs, a fluorescent lamp is generally used. The R, G, B emission spectrum of the backlight and transmission spectrum of the R, G, B color filters are

tuned together to achieve the desired color coordinates for the primary colors. Also, a diffuser is used to achieve uniform backlighting of the display. The backlight system may also use brightness enhancement films to tailor the light intensity distribution in the viewing cone. In addition to the above components, LCDs for specialized applications requiring enhanced performance may use a cover glass with EMI and antireflection coatings at the front, and a heater glass at the back side (between the backlight and the LCD) which facilitates low-temperature operation.

32.5 Liquid Crystal Display Modes

LC displays based on many different modes of operation have been developed. Historically, the phase change (PC) effect was discovered first in 1968 by Wysoki et al. [16]. The same year, dynamic scattering (DS) mode [17] and guest–host (GH) mode [18] were announced by Heilmeier et al. Then in 1971, the TN mode [19] was reported by Schadt and Helfrich and electrically controlled birefringence (ECB) was reported by Schiekell and Fahrenschon [20] and Hareng et al. [21]. The physical effects and the various display modes based on these effects include

- | | |
|-------------------------|-----------------------|
| Current effects: | • DS effect |
| Electric field effects: | • TN effect |
| | • STN effect |
| | • ECB |
| | • GH effect |
| | • Phase change effect |
| Thermal effects: | • Smectic effect |

The DS effect is based on the anisotropy of the conductivity. Because of higher voltage operation and higher power consumption, the DS mode is not currently used. The TN and STN effects are most widely used among all the LCDs. The following will discuss various display modes.

Twisted Nematic Effect

Figure 32.10 shows a schematic of a display based on the TN effect. It consists of nematic LC material with a positive dielectric anisotropy ($\Delta\epsilon > 0$) with a layer thickness of about $5\ \mu\text{m}$, sandwiched between two transparent substrates with transparent electrodes. The surfaces of the transparent electrodes are

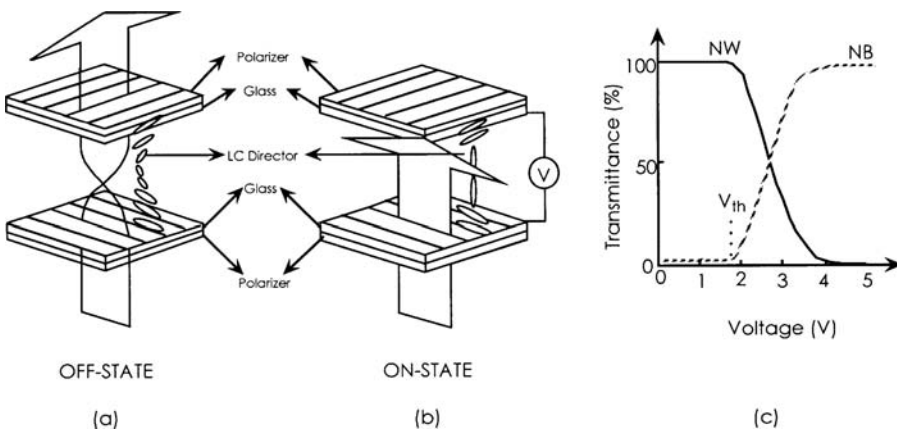


FIGURE 32.10 Illustration of TN effect: (a) in the off-state, the incident polarized light is transmitted through the entrance polarizer, the 90° TN LC, and the crossed exit polarizer; (b) in the on-state; (c) the solid line shows the voltage-transmission behavior for the NW configuration, shown in (a) and (b), with crossed polarizers. The dashed line is for an NB configuration with parallel polarizers.

coated with a polyimide alignment layer and rubbed to orient LC molecules at the substrate surfaces along the rubbing direction with a small ($\sim 3^\circ$) pretilt angle. The molecules on the two substrates are oriented 90° from each other as shown in Figure 32.10a; i.e., the LC molecular axis rotates (twists) continuously through 90° from the first substrate to the second substrate. The TN display can be fabricated to operate in a normally black (NB) or normally white (NW) mode based on how the polarizers are attached to the outer surface of the two glass substrates. Figure 32.10a and b shows the on- and off-state of a NW mode TN LCD with crossed (orthogonal) polarizers attached with their polarization direction parallel to the LC director orientation on that substrate. Since the pitch of the twist is sufficiently large compared with the wavelength of the visible light, the direction of polarization of linearly polarized light incident normally on one surface of the display rotates through 90° by the twist of the LC molecules as it propagates through the cell and exits through the second polarizer. When a voltage is applied to the TN cell, the molecules align parallel to the direction of the field as shown in Figure 32.10b, and the 90° optical rotatory power is eliminated. Thus, the incident polarized light from the first polarizer is not rotated as it goes through the LC cell and gets blocked by the crossed exit polarizer.

Figure 32.10c shows the voltage-transmission characteristics of a TN cell for NB and NW modes of operation. For an NW mode, when a sufficiently high voltage is applied, LC molecules are aligned homeotropically (parallel to the field) and there is no rotation of the electrical field vector of the polarized light. This results in complete suppression of transmission regardless of the wavelength of light. The transmission in the on-state is, however, wavelength dependent, but this does not have a significant effect on the contrast ratio, although it can influence the color balance. In the NB mode of operation, the transmission is suppressed to zero [22] for the off-state only for a monochromatic light of wavelength. Therefore, in a practical display using a broadband backlight, there is a small amount of light leakage which lowers the display contrast ratio. In a color display, the cell gaps for the R, G, B pixels can be optimized to eliminate the light leakage and improve contrast [22].

The threshold voltage of a TN mode LCD is given by

$$V_{th} = \pi \cdot \sqrt{\left\{ \left[K_{11} + (K_{33} - 2K_{22})/4 \right] / \epsilon_0 \cdot \Delta\epsilon \right\}} \quad (32.11)$$

V_{th} depends on the dielectric anisotropy and elastic constants, and is generally in the range of 2 to 3 V, with the maximum operating voltage being in the range of 5 to 8 V. This low voltage driving, coupled with low current due to high resistivity of LC materials, contributes to the very low power consumption ($\sim 1 \mu\text{W}/\text{cm}^2$) of LCDs. The response times measured by the rise and decay times of the display τ_r , τ_d , are given by [23]:

$$\tau_d = \gamma d^2 / \Delta\epsilon (V^2 - V_{th}^2) \quad (32.12)$$

$$\tau_r = \gamma d^2 / (\Delta\epsilon \cdot V_{th}^2) \quad (32.13)$$

where γ is the rotational viscosity coefficient. The above equations show that rise time can be improved by using a thinner cell gap d , a higher $\Delta\epsilon$, and a higher drive voltage V . Similarly, the decay time can be improved by reducing the cell gap. The turn-on time τ_r is usually shorter than the turn-off time τ_d . At room temperature, these times are of the order of 10 ms, which is adequate for many common applications such as computer and TV displays. In a TN LCD, gray scale is generated by varying the voltage using the electro-optic curve shown in Figure 32.10c. The shallow slope of the electro-optic curve works well for the gray scale generation in active matrix-addressed displays (see next section). However, in the case of passive matrix addressing, the shallow slope greatly limits the multiplexability (number of addressable rows) of the display, which led to the development of the STN effect.

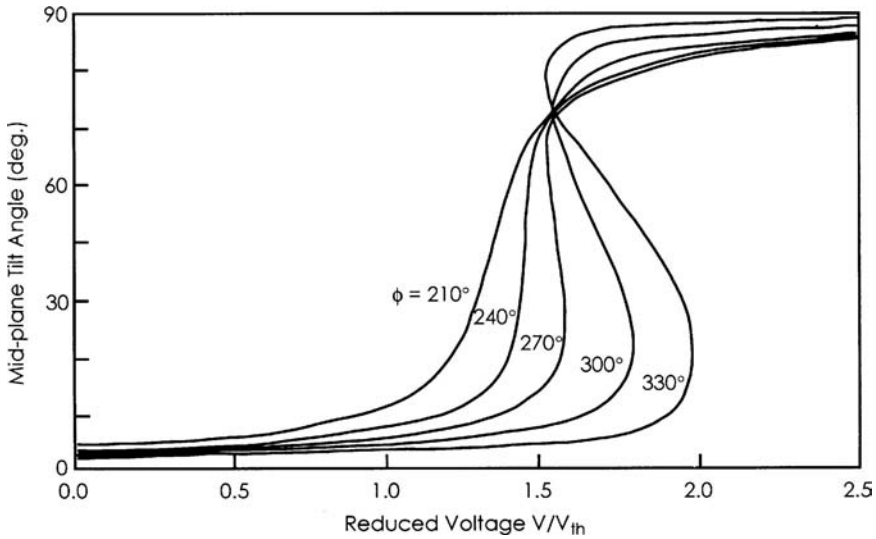


FIGURE 32.11 Calculated curves of tilt angle of local directors in the midplane of an STN cell as a function of reduced voltage V/V_{th} , where V_{th} is the Freedericksz threshold voltage of a nontwisted layer with a zero pretilt angle. The steepness of the curves increase as the twist angle, Φ , is increased, and bistability is achieved when $\Phi > 240^\circ$.

STN Effect

In a passive matrix-addressed display, the addressability or the maximum number of addressable rows N is given by the Alt and Pleshko [24] limit:

$$V_{on}/V_{off} = \sqrt{(N^{1/2} + 1)/(N^{1/2} - 1)} \quad (32.14)$$

where V_{on} and V_{off} are the rms voltages at the select and nonselect pixels. Equation 32.14 shows that as N increases, V_{off} approaches V_{on} and the contrast ratio becomes 1, which makes the display not viewable. For $N = 100$, $V_{on} = 1.11V_{off}$; i.e., select voltage is only 11% higher than the nonselect voltage. This will result in a very low contrast ratio when using a TN mode with a shallow turn-on curve (Figure 32.10c). STN displays have been developed [25, 26] to achieve a steep electro-optic curve, so that large numbers of rows can be multiplexed. The STN effect uses a twist angle of 180° to about 270° with a relatively high pretilt angle alignment. Figure 32.11 [25] illustrates the STN effect. The figure shows the voltage dependence of the midplane director tilt of a chiral nematic layer with a pretilt of 28° at both substrates. Bistability is achieved when a twist angle, Φ , greater than 245° is used. In highly multiplexed displays twist angles in the range of 240° to 275° and tilt angles in the range of 5° to 30° are generally used. High pretilts ensure that competing distortional structure which has 180° less twist is eliminated. For a 270° left-handed twist, optimum results are achieved when the front polarizer is oriented with its polarization axis at 30° with the LC director and the rear polarizer is oriented at an angle of 60° with the projection of the director at the rear substrate. Due to interference of the optical normal modes propagating in the LC layer, the display has a yellow birefringence color in the nonselect state (yellow mode). Rotation of one of the polarizers by 90° results in a complementary image with a bright colorless state, and a blue nonselect state (blue mode). White-mode STN displays are made using retardation films. The response time of a typical STN display is on the order of 150 ms. These displays typically have a lower contrast ratio and a narrow viewing angle.

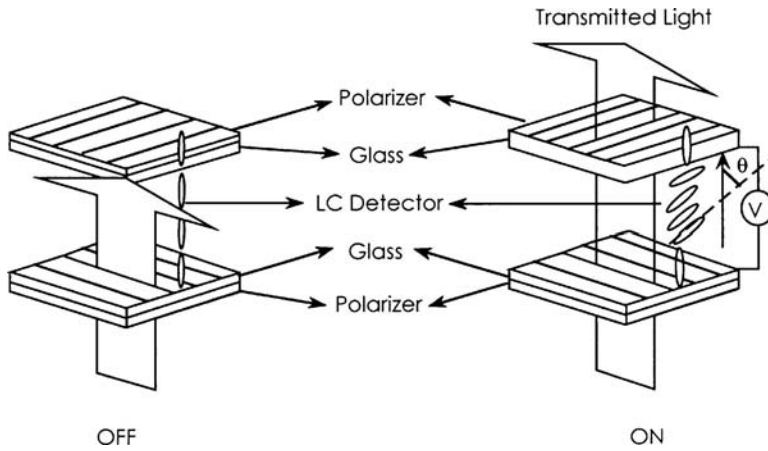


FIGURE 32.12 Illustration of an ECB display: (a) with homeotropic alignment and crossed polarizers, the off-state is black; (b) in the on-state, the output light through the LC is elliptically polarized due to the LC birefringence and the light is transmitted through the crossed polarizer.

Electrically Controlled Birefringence (ECB)

This display technique is based on controlling the birefringence of the LC cell by application of an electric field. There are a number of types of this display depending on the molecular orientation of the LC cell used; examples include DAP type, homogeneous type, HAN (hybrid aligned nematic) type, and IPS (in-plane switching) type. A DAP type (homeotropic orientation) is made using an LC with a negative $\Delta\epsilon$, sandwiched between transparent electrode substrates and placed between crossed polarizers, as shown in Figure 32.12. In the off-state (with no electric field), the incident polarized light does not see birefringence when passing through the cell, and thus gets blocked by the crossed exit polarizer. In the on-state (when a voltage is applied), the molecular axis of the LC is inclined at an angle θ (as shown in Figure 32.12), so the linearly polarized light becomes elliptically polarized as it passes through the cell due to birefringence. Hence a portion of the light passes through the crossed exit polarizer; the intensity I of the transmitted light through the cell is given by [20]

$$I = I_0 \sin^2 2\theta \cdot \sin^2 (\pi d \Delta n(V) / \lambda) \quad (32.15)$$

where I_0 is the intensity of the incident light, θ is the angle between the direction of polarization of the incident light and the direction of oscillation of the ordinary light within the cell, d is the cell spacing, $\Delta n(V)$ is the birefringence of the cell, $d\Delta n$ is the optical phase difference, and λ is the wavelength of the incident light. The equation shows that I depends on the applied voltage and λ .

In case of the homogeneous technique, the LC cell uses positive material with a homogeneous orientation. With this method, the threshold voltage is obtained by replacing the bend elastic coefficient K_{33} , with splay elastic coefficient K_{11} . The HAN cell is characterized by a hybrid orientation cell in which the molecules are aligned perpendicular to one substrate, but parallel to the second substrate. In this mode, both positive and negative $\Delta\epsilon$ materials can be used, and since there is no clear threshold voltage, it has the advantage of a very low drive voltage. Recently, an ECB mode based on an IPS type display has been developed to produce LCDs with extremely wide viewing angles. In the IPS mode displays, LC is homogeneously aligned and switched between on- and off-states using interdigitated electrodes fabricated on one of the display substrates [27]. The IPS mode displays use an NB mode with either positive or negative $\Delta\epsilon$ LC materials.

Guest–Host Type

Some organic dyes show anisotropy of light absorption; i.e., they absorb more light in a specific wavelength band when the **E** vector of the light is parallel to the optic axis of the dye molecules, than they do when it is perpendicular. LCDs based on this principle are called guest–host (GH) displays. In these displays a small amount of a dichroic dye (guest) is mixed in the LC material (host). These dye molecules get aligned to the LC molecules; hence, their orientation can be changed (by changing the orientation of the LC molecules) by application of an electric field. When an LC material with a positive $\Delta\epsilon$ is used, in the off-state, the **E** vector of the polarized light coincides with the light absorption axis of the dichroic dye; hence, light is absorbed and transmitted light is colored. When a voltage is applied for the on-state, the **E** vector of the polarized light is orthogonal to the absorption axis of the dye; hence, no absorption takes place, and transmitted light is not colored (white). GH LCD requires only one polarizer. Further, because the optical effect is based on absorption, the display provides a better viewing angle than a TN mode LCD.

Phase-Change Type

The phase change type of display is based on a change in molecular orientation from a helical cholesteric phase to a homeotropic nematic phase, and vice versa. For this technique, a cholesteric LC with a long helical pitch with a positive or negative $\Delta\epsilon$ is used. No polarizers are used in this display. In the off-state of this display, the incident light passing through the cholesteric cell with a focal conic orientation is optically dispersed (scattered), and the cell looks cloudy. However, when a voltage is applied, helical structure of the cholesteric phase changes to a nematic phase with a homeotropic orientation, and the cell becomes transparent.

Thermal Effects

Thermal effect is based on a change in the electro-optical behavior due to a change in the molecular orientation of the LC when it is heated or cooled. This effect is utilized with smectic LCs with a homeotropic alignment. When this cell is heated until the isotropic phase is reached and cooled, then if the cooling is sudden, the cell becomes cloudy, whereas if the cooling is gradual, the cell becomes transparent. These cloudy and transparent states correspond, respectively, to the focal conic and homeotropic orientations of the smectic A LC. This effect is used for large-size memory type displays, in which a laser beam is used to write the image thermally. The heating can also be accomplished by one of the transparent electrodes, while the other transparent electrode is used as a signal electrode.

32.6 Display Addressing

Display addressing (driving) techniques have a major influence on the LCD image quality. The addressing techniques can be classified in three essential types, namely, direct (static) addressing, passive matrix addressing, and active matrix addressing. In the case of low-information-content displays such as numeric displays, bar graph displays, and other fixed pattern displays, using segmented electrodes, direct addressing is used. A common example of direct-addressed displays is a numeric display using seven segmented electrodes for each digit. Each of these segmented electrodes on the front substrate and the common electrode on the back substrate are directly connected to drive signals. A voltage is selectively applied to each of the segments so that any of the digits between 0 and 9 can be displayed. For high-information-content displays, this approach becomes impractical because of the huge number of interconnects, and, hence, either passive matrix or active matrix addressing is used.

Passive Matrix Addressing

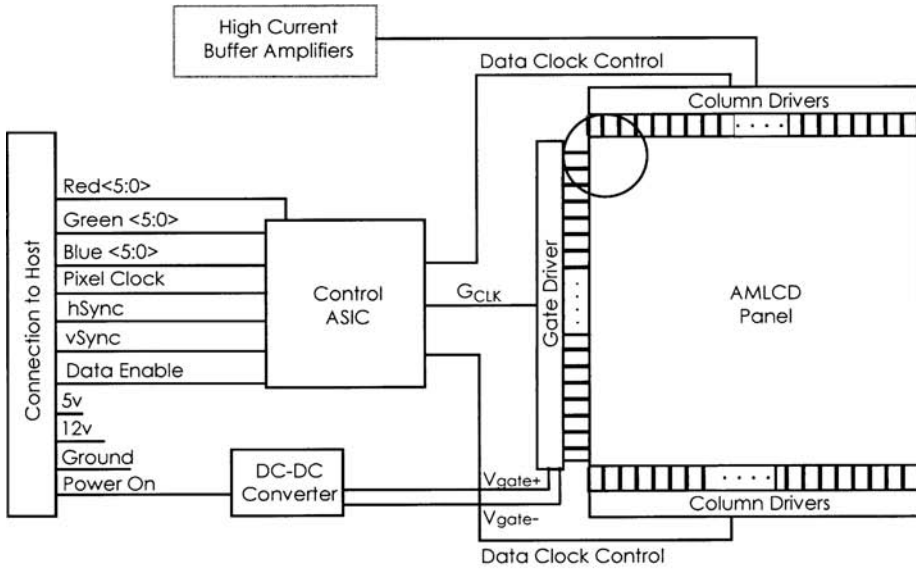
A passive matrix (PM) display comprising an LC between a matrix of transparent conducting row and column electrodes (Figure 32.8) is the simplest and least expensive matrix-addressed LCD to manufacture.

An example of a PM LCD is a color (R,G,B) VGA (video graphics array) display using the STN effect, with a pixel format of $640 (\times 3 = 1920) \text{ H} \times 480 \text{ V}$, with 1920 columns and 480 rows, for a total of 2400 interconnects used for addressing a display containing 921,600 pixels. In PM addressing, the row voltages are scanned in succession with a voltage, V_p , while all the columns in a given row are driven in parallel, during the row time, with a voltage of $\pm V_c$ depending on whether the pixel is selected to be ON or OFF. As discussed above under the STN effect, the contrast ratio of PMLCDs is influenced by the Alt and Pleshko [24] addressability limitation. To enhance the operating margin for improved contrast ratio, DSTN (dual-scan STN) configuration is used in higher-information-content displays. In a DSTN, the display is separated into two halves, and the rows in each half are scanned simultaneously and synchronously, to essentially double the duty ratio of the ON pixels to increase the contrast ratio. One of the major shortcomings of the passive matrix-addressed STN display is the slow response time of the LC, which is of the order of 150 ms. This slow response time is not adequate for video applications and is barely fast enough for the graphical interface of a computer. The response time of the STN LCDs can be improved by active addressing or multiline addressing techniques [28, 29]. These techniques involve simultaneous addressing of several rows of a display to suppress the frame response problems of conventional STN LCDs.

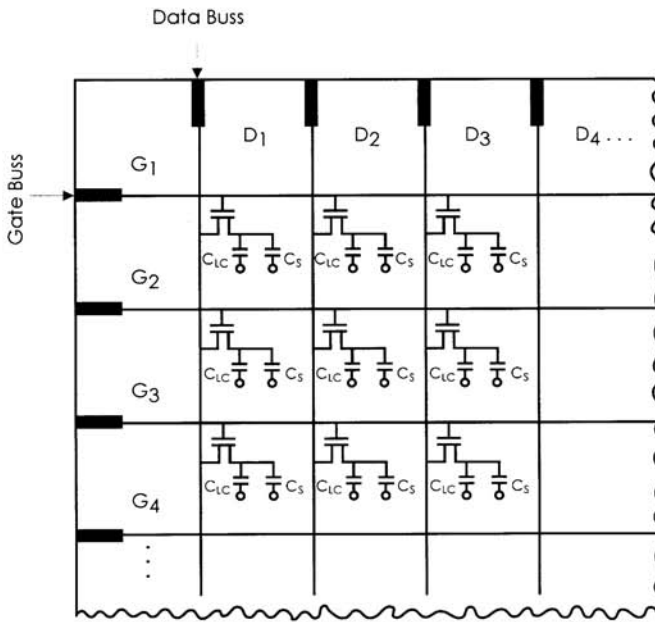
Active Matrix Addressing

Active matrix (AM) addressing removes the multiplexing limitations [24] of the PM LCDs by incorporating a nonlinear control element in series with each pixel, and provides 100% duty ratio for the pixel using the charge stored at the pixel during the row addressing time. Figure 32.13a illustrates an active matrix array with row and column drivers and the associated display module electronics. Figure 32.13b shows a magnified view of the active matrix array in the AM LCD panel. In the figure, C_{LC} and C_s represent the pixel capacitance and the pixel storage capacitance. Typically, a storage capacitor, C_s , is incorporated at each pixel to reduce the pixel voltage offset (see Equation 32.16 below) and for a broad temperature operation. Figure 32.14 shows the cross section through an AM LCD illustrating various elements of the display. Figure 32.15 shows a typical AM LCD pixel, showing the gate and data busses, thin-film transistor (TFT), ITO pixel electrode, and the storage capacitor. Fabrication of the active matrix substrate is one of the major aspects of AM LCD manufacturing. Both two-terminal devices such as back-to-back diodes, and metal-insulator-metal (MIM) diodes as well as three-terminal TFTs are developed for active matrix addressing. While two-terminal devices are simple to fabricate and cost less, their limitations include lack of uniform device performance (breakdown voltage/threshold voltage) over a large display area, and lack of total isolation of the pixel when neighboring pixels are addressed. For a superior image quality AM LCDs use TFT for the active matrix device, which provides a complete isolation of the pixel from the neighboring pixels. Large-area AM LCDs use amorphous silicon (a-Si) TFTs [6], while polysilicon TFTs with integrated row and column drivers are used in small high-resolution LCDs [30].

Figure 32.16 shows the electric equivalent of a TFT-LCD pixel, display drive waveforms, and the resulting pixel voltage. As in most matrix-addressed displays with line-at-a-time addressing, the rows (gates) are scanned with a select gate pulse $V_{g,sel}$, during the frame time t_f , while all the pixels in a row are addressed simultaneously with the data voltage $\pm V_d$ during the row time $t_r (= t_f/N)$. During the row time the select gate voltage, $V_{g,sel}$, “turns on” the TFT and charges the pixel and the storage capacitor to the data voltage V_d . After the row time, the TFT is “switched off” by application of the nonselect gate voltage, $V_{g,non-sel}$; hence, the voltage (charge) at this pixel is isolated from the rest of the matrix structure until it is time to charge the pixel during the next frame time. Note that the LC pixel must be driven in an ac fashion with $+V_d$ and $-V_d$, during alternate frame periods, with no net dc across the pixel. A net dc voltage across the pixel results in flicker and image sticking effects [33], resulting from LC conductivity. Large and sustained dc voltages also degrade the LC material due to electrolysis. The shift in pixel voltage, ΔV_p shown in Figure 32.16, at the end of the row time is due to the parasitic gate-to-drain capacitance, C_{gd} , of the TFT. When the gate voltage is switched, the distribution of the charge from the TFT gate dielectric causes the pixel voltage shift ΔV_p , given by



(a)



(b)

FIGURE 32.13 (a) AM LCD module electronics block diagram; (b) magnified view of the region shown in (a) illustrating active matrix TFT array.

$$\Delta V_p = (\Delta V_g) C_{gd} / (C_{gd} + C_{lc} + C_s) \quad (32.16)$$

For the n -channel enhancement mode a-Si TFT, this voltage shift ΔV_p is negative for both the positive and negative frames; thus, it helps pixel charging in the negative frame and hinders it in the positive frame. Further, due to increased gate bias during the negative frame, the pixel attains the data voltage

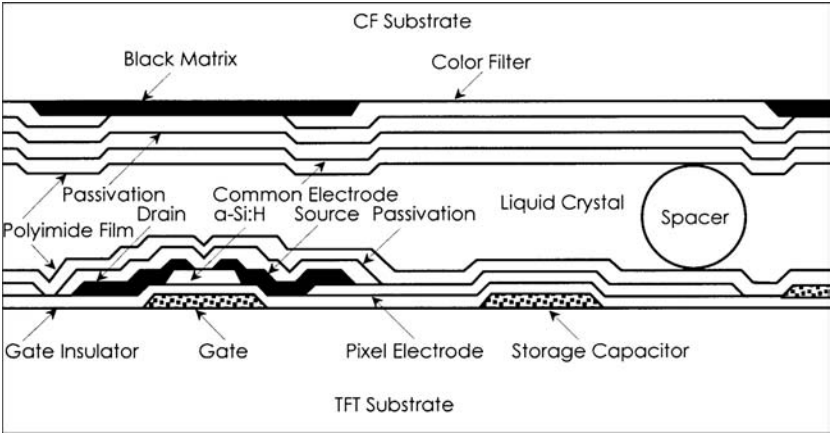


FIGURE 32.14 Cross-sectional view through an AM LCD showing TFT, pixel electrode, storage capacitor, polyimide alignment layers, color filter, and black matrix.

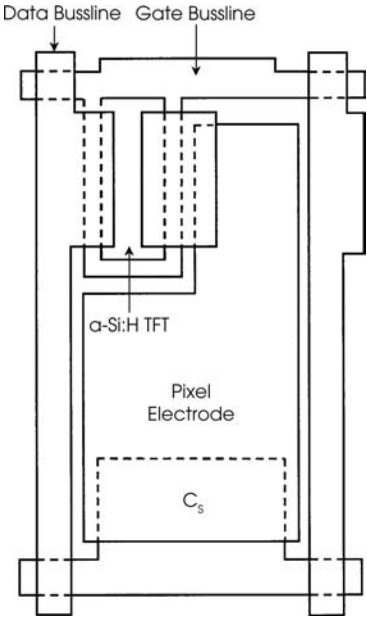


FIGURE 32.15 Layout of a pixel in a TFT-LCD showing the TFT, pixel electrode, and storage capacitor.

much more rapidly during the addressing period. Hence, the TFT is designed for the worst-case positive frame conditions. ΔV_p is reduced by minimizing C_{gd} by decreasing the source drain overlap area of the TFT and by using a storage capacitor. Further, ΔV_p is compensated by adjusting the common electrode voltage V_{com} as shown in Figure 32.16. Note that C_{lc} is a function of the V_p (V_{lc}) due to the dielectric anisotropy of the LC; and hence, adjustment to V_{com} alone does not eliminate dc for all gray levels, and modification of the gray scale voltages is required to compensate for the dielectric anisotropy of the LC.

Display Module Electronics

Figure 32.13 shows a block diagram for an AM LCD module electronics. The control block and power supply generation means are separately mounted on a PC board and connected to the row and column

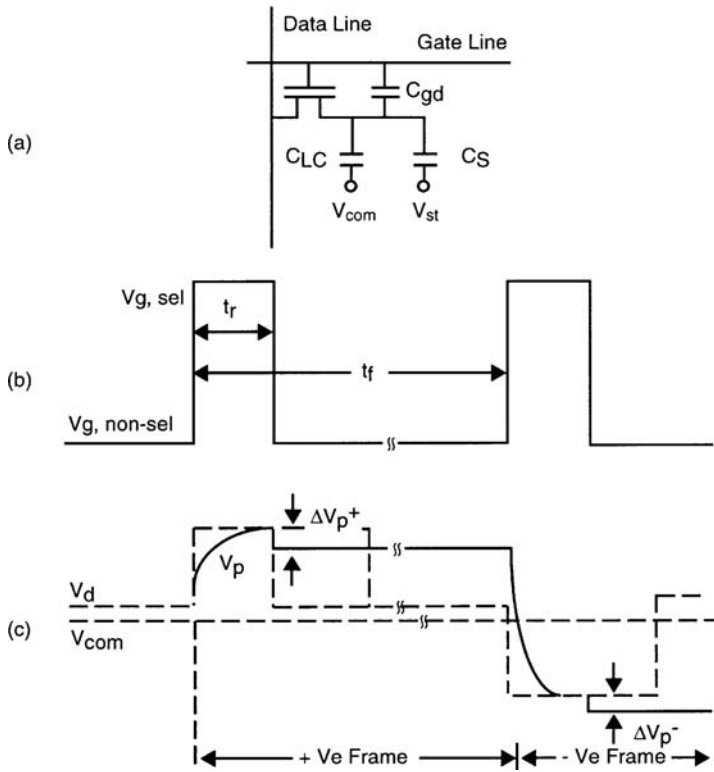


FIGURE 32.16 (a) Electric equivalent of a TFT-LCD pixel; (b) gate drive voltage waveform; (c) data voltage waveform and pixel charging behavior in the positive and negative frames.

drivers of the LCD on one side and to the host controller on the other. The control block may include level shifters, timing generators, and analog functions in some cases; the control block takes in digital data from the host system, which is typically a graphics controller chip, and converts it into timing and signal levels required by the row and column drivers. The architecture and design of the module electronics encompassing row and column drivers have a significant impact on not only the display system cost and power consumption, but also the image quality. The LC material typically requires about 5 V to achieve optical saturation (see Figure 32.10c). Considering the need for an ac drive, the required voltage swing across the LC material is about 10 V. To achieve this 10 V swing across the LC material, the column drivers typically use 12 V power supplies. Column driver voltage can be reduced by using a V_{com} modulation drive method. In this method, the V_{com} node (which is connected to all pixels in the display) is driven above and below a 5 V range of the column drivers. Each and every row time, the V_{com} node is alternated between a voltage above and a voltage below the 5 V output range of the column drivers. This achieves 10 V across the LC material using 5 V column drivers. This method requires additional components and consumes additional power due to the oscillation of the V_{com} node. In addition, to avoid capacitive injection problems, the row drivers usually have their negative supply modulated with the same frequency as the V_{com} node. Note, however, that compared to 10 V column drivers, 5 V column drivers consume less power, and are simpler to design and fabricate using small-geometry CMOS. The V_{com} modulation drive method can be used with a row (polarity) inversion scheme only (for elimination of pixel flicker) which results in some horizontal cross talk. However, column inversion and pixel inversion schemes provide better image quality with much-reduced cross talk, but they cannot be used with the V_{com} modulation drive.

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