

CHAPTER I

INTRODUCTION

1.1.Introduction:

Liquid crystal materials are mainly used in the world's dominant mode of information display called Liquid Crystal Display (LCD), which is rapidly replacing other display media and is clearly established as one of the world's top few industrial technologies. The development of new liquid crystal (LC) compounds requires innovative and comprehensive knowledge in the entire range of multidisciplinary topics associated with the science and technology. Certain organic materials exhibit the liquid crystalline state as the transition between the solid and the liquid states, known as mesophases. These materials therefore combine the flow properties of liquids along with the optical properties of crystals. Shape anisotropy in these organic materials with the lengths of the molecules several times larger than their breadth is the dominant factor which gives rise to liquid crystalline behavior. An Austrian botanist Friedrich Reinitzer [1] probably was the first person to perform research on liquid crystals. Around 150 years ago in 1888 he conducted an experiment involving a material known as cholesterol benzoate, where he observed that on heating the solid sample it first changed into a hazy liquid and then transformed into a transparent liquid. A physics professor named Otto Lehmann [2] having learned of Reinitzer's discovery, conducted his own research confirming that the substance seem to have two distinct melting points. His research led him in 1889 to coin the term 'liquid crystal' for this class of substances. The liquid

crystalline phases are also termed as mesophases. Between the crystalline solid and isotropic liquid several mesophases may exist. Of these, the simplest is the nematic phase [3, 4] which happens to find the widest application in the field of Liquid Crystal Displays (LCD's). In this phase, there is no correlation between the molecular centers of gravity, but the direction of the molecular long axis do statistically have a favoured direction called the director \hat{n} . Other higher ordered phases like the smectic A [5], characterized by an additional one dimensional layer-like density wave fluctuation superimposed on the orientational ordering on these systems, also exist. In addition to several organic chemicals that exhibit mesophases [6, 7] few organo-metallic [8, 9] and inorganic chemicals [10] also show liquid crystalline properties as well.

The unique combination of order and mobility in these systems and the easy response of these materials to electric, magnetic and surface forces have generated many applications in the field of displays ranging from mobile phones, laptop computers to high resolution TV displays and projection systems. Very recently, efforts have been made to develop a 4k compatible Liquid Crystal on Silicon (LCoS) device [11] for digital cinema [12], medical imaging [13] and simulation applications [14]. The major driving force for the research and development in the field of liquid crystals is due to the fact that LCD's enjoy the key advantages of flatness and compactness leading to lighter weight and significant reduction in power consumption in comparison to the Cathode Ray Tubes (CRTs). There are several books and reviews on liquid crystals which give details regarding molecular structure and physical properties of the compounds exhibiting mesophases of which a few [15-24] are listed here. Recent development in the field of liquid crystals and applications are also available [25-35].

1.2. Classification of Liquid Crystals:

Liquid crystals are broadly classified into two types, viz. lyotropic and thermotropic.

1.2.1. Lyotropic Liquid Crystals:

Lyotropic liquid crystals belong to a class of substances called amphiphilic compounds (surfactant). One end of the molecule is polar and attracted to water (hydrophilic), while the other end is nonpolar and attracted to hydrocarbons (lipophilic). As the concentration of the molecules in solution increases, they take on different arrangements or phases – lamellar, cubic and columnar (Figure 1.1). The amount of solvent is the controlling parameter for forming such mesophases. Solution of soap and water are typical examples of lyotropics and their mesomorphic properties appear both as a function of concentration and temperature. Lyotropic liquid crystals have relevance in biological systems like bio-membranes and also in certain proteins which exhibit liquid crystalline properties.

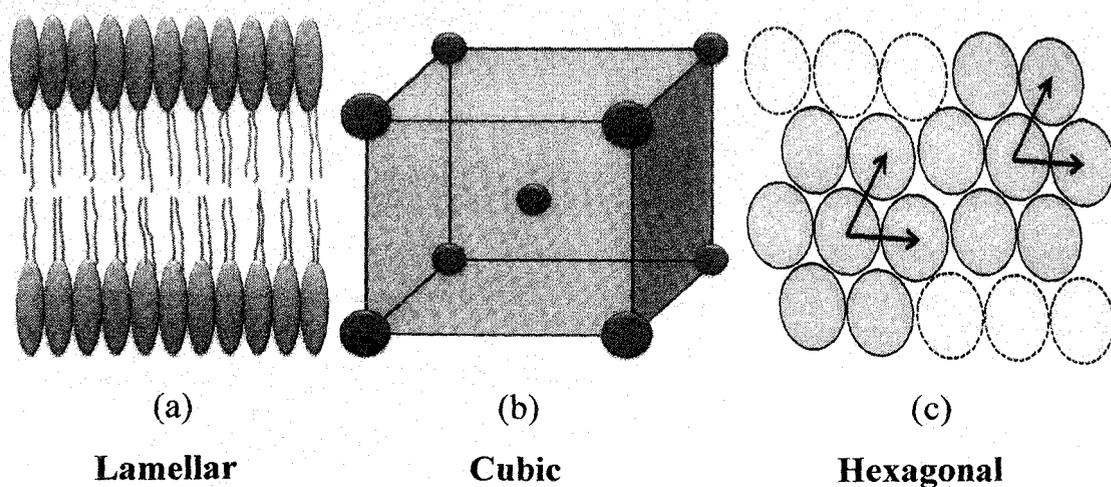


Figure 1.1. Different kinds of lyotropic liquid crystals: (a) Lamellar, (b) Cubic and (c) Hexagonal.

1.2.2. Thermotropic Liquid Crystals:

In thermotropic liquid crystals, mesomorphic behaviour is induced due to change in temperature (Figure 1.2). The vast majority of thermotropic liquid crystals are composed of rod-like molecules (one molecular axis is longer than the other two) [36, 37].

Thermotropic liquid crystals that exhibit reversibility of phase transition are called 'enantiotropic'; in certain cases mesomorphism is observed only during cooling and these transitions are called 'monotropic' transitions.

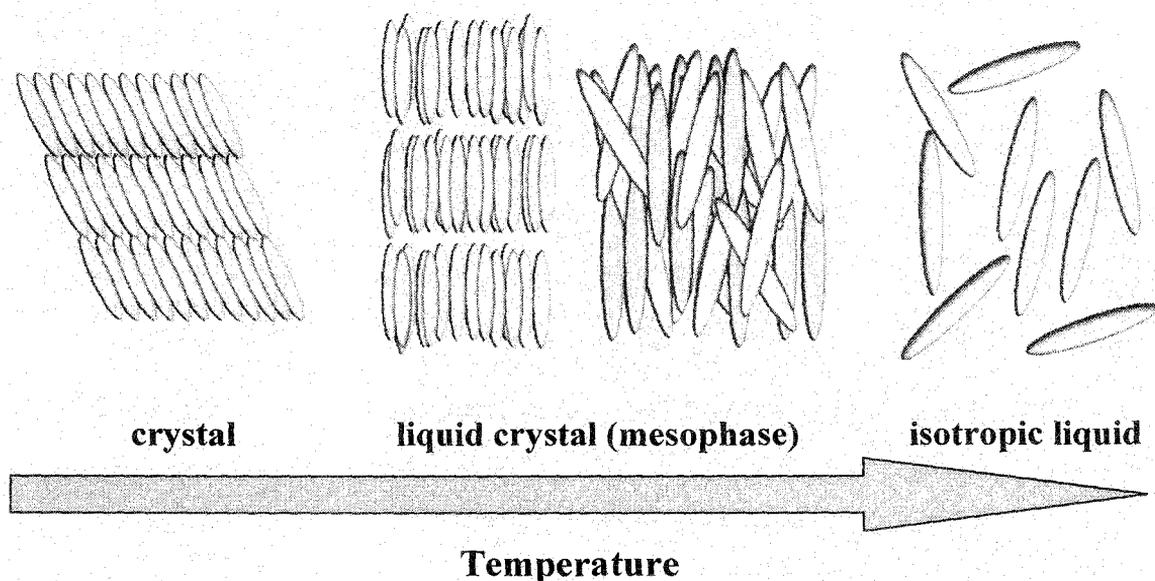


Figure 1.2. Phase transitions of a typical rod like liquid crystal material with increase in temperature.

Friedel [38] from his detailed optical and x-ray studies have classified thermotropics into three main types: nematic, cholesteric and smectic. Classification of smectic liquid crystals are based mainly on the optical and miscibility studies of Sackmann and Demus [39]. A brief description of different thermotropic mesophases are given below.

1.2.3. Nematic (N) phase:

In nematic liquid crystals, [3, 4] there is no positional and translational order of the center of mass of the rod-like molecules. The molecules however

are spontaneously oriented with their long axes approximately parallel to a preferred direction called the director. The preferred direction usually varies from point to point in the medium, but a homogeneously aligned specimen is optically uniaxial and strongly birefringent. Since there is no restriction regarding the positions of the centre of mass, the molecules in this phase have a high degree of mobility. Deformation in the alignment of the nematic molecules can be translated into visible optical effects by even small external electrical, magnetic and mechanical influences, for which they are extremely useful in various display devices. The ordinary nematics show an optically positive uniaxial behaviour, but a biaxial modification has also been discovered [40]. Another characteristic property of this phase is that the mirror images of the molecules are indistinguishable, i.e., achiral, indicating the system to be a racemic mixture of right- and left-handed molecules. The molecules are able to rotate about their long axes and there is no preferential arrangement of the two ends of the molecules. A simplified picture of the relative arrangement of the molecules in the nematic phase is shown in Figure 1.3. The long planar molecules are symbolized by ellipses.

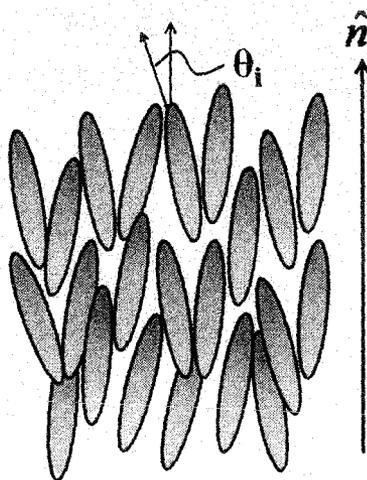


Figure 1.3. Schematic diagram of the nematic (N) phase. The spatial and temporal average of long molecular axis is called the director \hat{n} . The angle θ_i denotes the deviation of the long molecular axis of an individual mesogen i from the director.

1.2.4. Cholesteric or chiral nematic (N^*) phase:

The cholesteric (or chiral nematic) liquid crystal phase [41-43] is typically composed of nematic mesogenic molecules containing a chiral center, which produces intermolecular forces that favour alignment between molecules at a slight angle to one another. This leads to the formation of a structure that can be visualized as a stack of very thin two-dimensional nematic-like layers with the director in each layer twisted with respect to those above and below it. So the directors actually form a continuous helical pattern about the layer normal as shown in Figure 1.4. This twist is due to the presence of one or more chiral centers within the molecules.

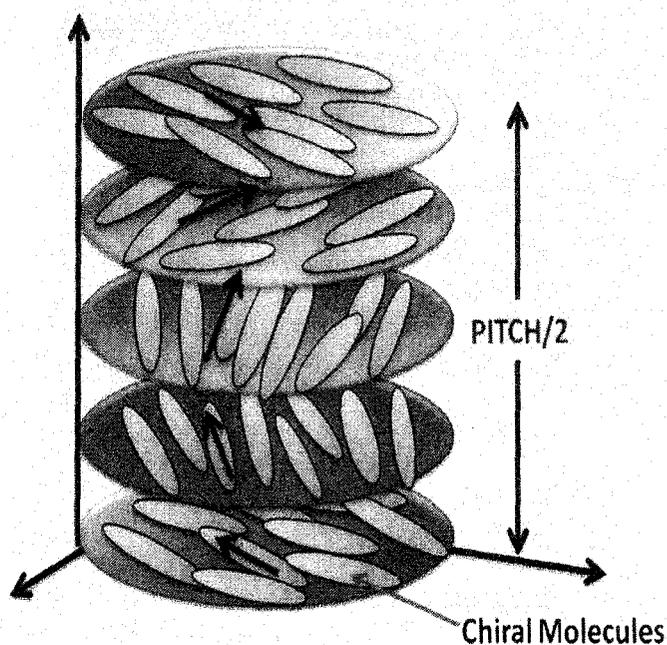


Figure 1.4. Helical structure of the Cholesteric or chiral nematic (N^*) liquid crystal.

The helix [44] may be right handed or left handed depending on the molecular conformation. An important characteristic of the cholesteric mesophase is the temperature dependent pitch (p) which is defined as the distance it takes for the director to rotate one full turn in the helix. The helical structure of the chiral nematic phase enables it to selectively reflect light of

wavelengths equal to the pitch length. This property is utilized in liquid crystal thermometers. Cholesteric liquid crystals are not regarded as a separate phase but just as a nematic phase having a finite pitch.

1.2.5. Smectic Liquid Crystals:

Besides the orientational order of the long molecular axes found in the nematic phase, the smectic phase is characterized by the existence of an additional one-dimensional density wave. The molecular centers of mass on the average are arranged in equidistant planes. Within the layers the molecular centers lie in a single plane, while their long axes are either perpendicular or tilted relative to this plane. In both cases the arrangement of the centers of the molecules within each layer corresponds to a two dimensional liquid (i.e. the presence of short range order and absence of long range order).

The smectic liquid crystals [5, 45-53] are generally more viscous than nematics. The interlayer attractions are weaker than the lateral forces between the molecules and the layers can slide over each other, thus showing fluid like behaviour. In some smectic phases a periodicity characteristic of a two – dimensional solid is observed with respect to the position of the centers of mass of the molecules within each layer, while the molecular long axes remain either perpendicular or inclined to the plane of the layer [54-56]. A large number of smectic phases have been identified; some of them are listed below in the order of their possible appearance

Sm A, Sm C, Sm B, Sm D, Sm E, Sm F, Sm G, Sm H

Discussion on the different smectic modifications in this dissertation is limited only to the Sm A, Sm C and Sm B phase, since most of the compounds studied in this work exhibit nematic and a few either Sm A or Sm B phase.

1.2.6. Smectic A (Sm A) phase:

In smectic A (Sm A) phase [shown in Figure 1.5(a)], the molecular orientation is perpendicular to the layers. There is no positional order of the molecules within the layers and therefore the smectics are often considered as two-dimensional liquids. Normal to the layers, the molecules are essentially arranged in a one-dimensional density wave. In this phase usually the layer spacing (D) is approximately equal to the molecular length (l). However, other modifications are also possible – the monolayer smectic A (SmA_1), bilayer smectic A (SmA_2), partially bilayer smectic A (SmA_d) and smectic antiphase ($Sm\tilde{A}$) [57-60].

1.2.7. Smectic C (Sm C) phase:

The smectic C phase is very similar to the smectic A phase with a one dimensional density wave of orientationally ordered molecules [61-63]. However within the layers, the average orientation direction (\hat{n}) of the molecules which form the liquid crystals is tilted at an angle θ [shown in Figure 1.5(b)]. The layer spacing of the smectic C phase is less than that of the corresponding smectic A phase due to this tilt. For some materials the tilt angle is constant but for others it is temperature dependent. The centers of gravity of the molecules are randomly ordered and the molecules are free to rotate around their long axes. SmC phases are optically biaxial and also more viscous than smectic A phase. The tilted arrangement of the molecules within the layer is energetically more favourable.

1.2.8. Smectic B (Sm B) phase:

Smectic B phase has a layered orthogonal structure where the molecular long axes are arranged perpendicular to the layer normal. In each plane the molecules are arranged in a hexagonal pattern representing two dimensional

crystals. (Figure 1.5(c)). Thus an additional order parameter, i.e. bond order parameter [64] is needed to describe this phase.

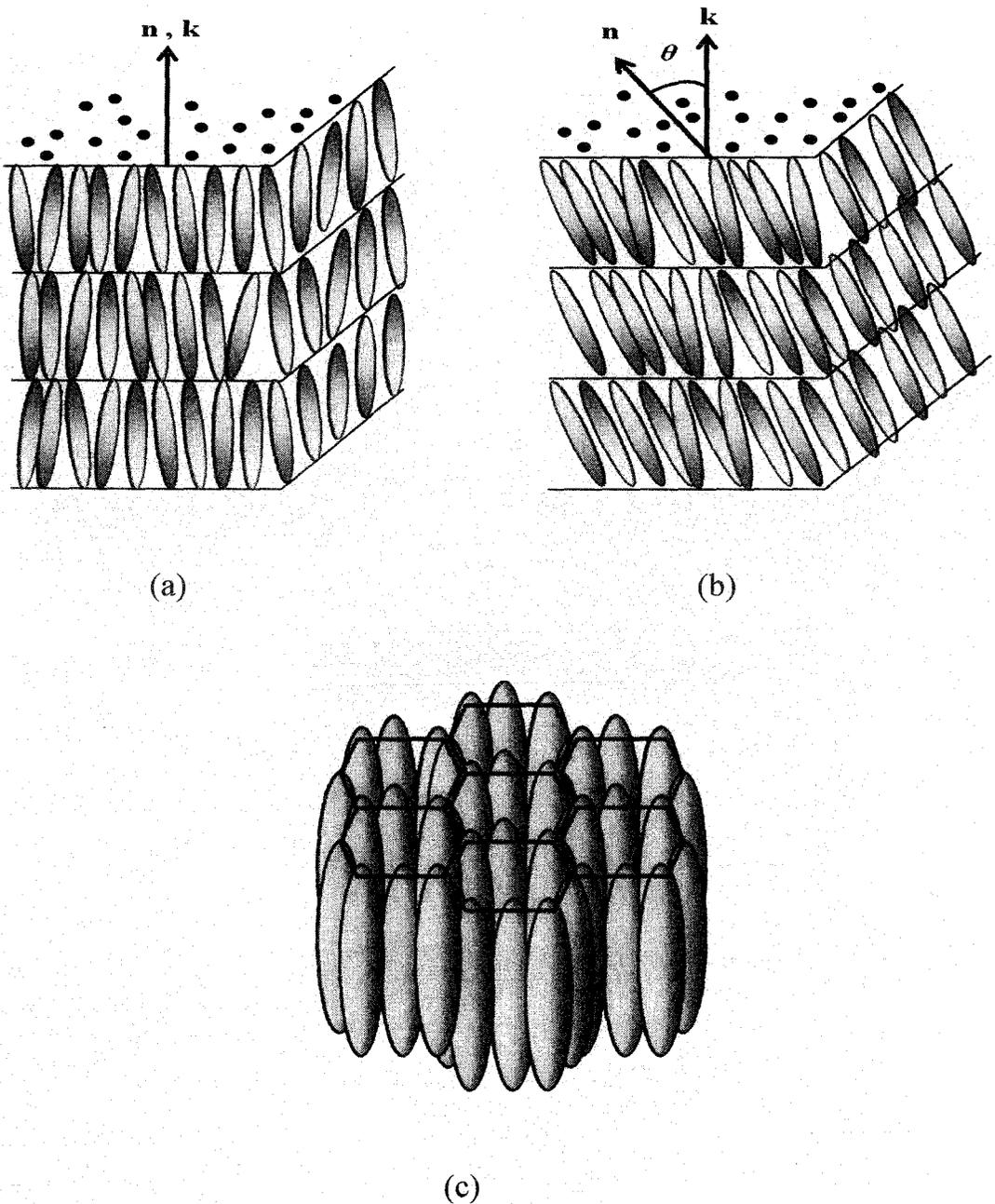


Figure 1.5. Model Structure of (a) Smectic A (Sm A) phase. The director \hat{n} is oriented parallel to the smectic layer normal \mathbf{k} , within a smectic layer the molecules' centre of mass are isotropically distributed. (b) Smectic C (Sm C) phase. The director \hat{n} is tilted with respect to the smectic layer normal \mathbf{k} by an angle θ , the director tilt angle, which is a temperature dependent quantity. The molecules' centers of mass within a smectic layer are isotropically distributed. (c) Smectic B (Sm B) liquid crystal.

On the basis of x-ray [65] and electron diffraction [66] experiments done on bulk aligned samples as well as on thin films, the smectic B phase can be further classified into - smectic B_{hex} and crystal B phase depending upon the presence of short range or long range translational order respectively. Due to the hexagonal arrangement of the molecules within the layers of smectic B phase, a highly co-ordinated or synchronized rotational motion of the molecules exist [67-69] such that the edge of one molecule is presented to the side of a neighbouring molecule. Due to this hindered rotation the smectic B phase may show optical biaxiality [40].

1.3. Other liquid crystalline phases:

1.3.1. Blue phase:

Blue phases has generally been observed in a very small temperature range ($\approx 0.1^\circ\text{C}$) between the cholesteric and the isotropic phase. Compounds exhibiting "blue phases" have a short pitch ($< 7000 \text{ \AA}$) and can display upto three different varieties of blue phases namely BPI*, BPII* and BPIII* in accordance with their thermal stability depending on their pitch. With the increase of the pitch, phase-III loses its stability first, then phase-II and lastly phase-I. These liquid crystalline materials display bluish-violet colour below its cholesteric-isotropic transition temperature [70-74]. The structures are explained in terms of defects in the cubical array. Blue phases stabilized at room temperature allow electro-optical switching with response times of the order of 10^{-4} s. [75]. Blue phases are also interesting for fast light modulators or tunable photonic crystals [76, 77].

1.3.2. Twist Grain Boundary Smectic A (TGBA) phase:

Goodby et al [78, 79] have discovered a new liquid crystal phase in 1989, called Twist Grain Boundary Smectic A (TGBA) phase, which consists

of smectic slabs separated by the defect walls, the neighbouring slabs being tilted with respect to each other leading to a helical structure. Within the slab the molecules are arranged in layers with their long axis perpendicular to the layer plane. Renn and Lubensky [80, 81] in their model specified that the molecules of TGBA phase are responsible for rotating each blocks of the chiral A* layers with respect to each other. Since then many new TGBA [82, 83] and TGBC [84, 85] phases have also been identified.

1.3.3. Ferroelectric Liquid Crystals:

R. B. Meyer [86] is known as the pioneer in the work regarding ferroelectricity of liquid crystals. In this phase the molecules are tilted from smectic layer normal. Due to the tilt, the rotation of the molecules about their long axes is not isotropic, resulting in a non-compensated macroscopic component of the molecular dipole moment. The ferroelectric smectic C* phase is analogous in structure to the smectic C phase except that the molecules possess chirality, resulting in a spontaneous "ferroelectric polarization". The chiral interactions lead to a twisted structure and consequently the polarization also has a helical arrangement. Ferroelectric liquid crystals are very important for fast switching electrooptical display devices. Additionally, ferroelectric [87] and anti ferroelectric phases [88] have also been discovered, where in the former the local dipole moments are partially compensated, while in the anti ferroelectric phase the molecules in the neighbouring smectic layers are tilted to the opposite direction, as a result of which the opposite dipole-moments in the next layers cancel to zero. Immense progress on Ferroelectric Liquid Crystal (FLC) Displays have been made in the last few years. The large possibilities of FLCs with fast bistable electrooptical effect, high speed, short response time and linear response with the field open a new horizon over more classical multiplexed technologies. Antiferroelectric liquid crystals may be switched into its two ferroelectric states

which are synclinic and synpolar [89] and are widely used in V-shaped switching, (which is characterized by thresholdless, domainless and hysteresis free behavior) [90]. Ferrielectric liquid crystals are utilized in different photonic display devices [91].

1.3.4. Discotic Liquid Crystals:

Chandrasekhar *et. al.* in 1977 reported for the first time thermotropic mesomorphism in pure compounds consisting of simple disc like molecules [92]. The disc like molecules can either arrange themselves in stacks one on top of the other like a pile of disordered plate forming the nematic phase or they may arrange themselves in columns one on top of the other thereby forming the columnar phases [shown in Fig. 1.6]. Depending upon the orientation of the different columns the columnar phase can be further subdivided in several groups such as hexagonal and rectangular columnar phases [93]. Significant research works have been performed for the last ten years on discotic liquid crystals [94, 95]. The self-assembly properties of discotic liquid crystals made them more desirable for manufacturing commercial electronic devices-Organic Light Emitting Diode (OLED) displays [96] and also in photovoltaic cells .

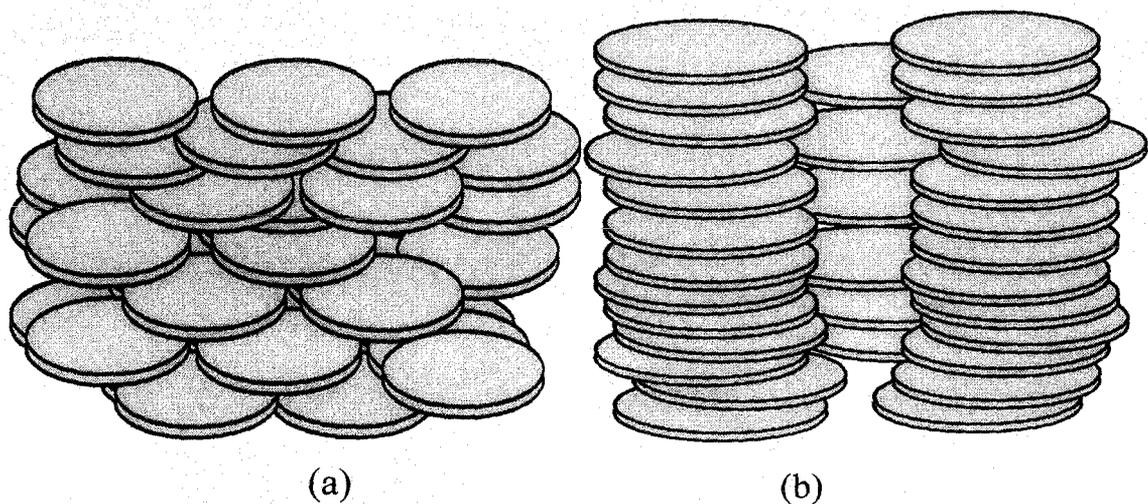


Figure 1.6. Schematic representation of (a) nematic and (b) columnar structure of discotic mesogens.

1.3.5. Polymer Liquid Crystals:

Certain polymers have structures that are responsible for the creation of liquid crystalline phases in them [97]. The monomer units are arranged as rods or discs and are attached to the polymer backbone in the main chain or they are attached as side groups as shown in Figure 1.7 and 1.8. The presence of these chained liquid crystals in a confined liquid crystal structure enables the main liquid crystal molecules to align with the chains of the polymer liquid crystals. Polymer liquid crystals are useful for liquid crystal stabilization. Application of appropriate voltage causes the nematic droplets to align in such a way that their refractive indices nearly match that of the polymer causing transparency. They are widely used in displays, switchable windows and other light shutter devices [98, 99].

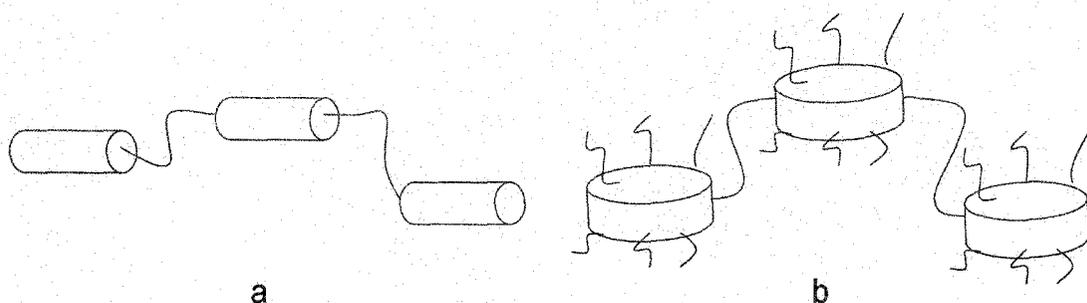


Figure 1.7. Main chain polymer liquid crystal.

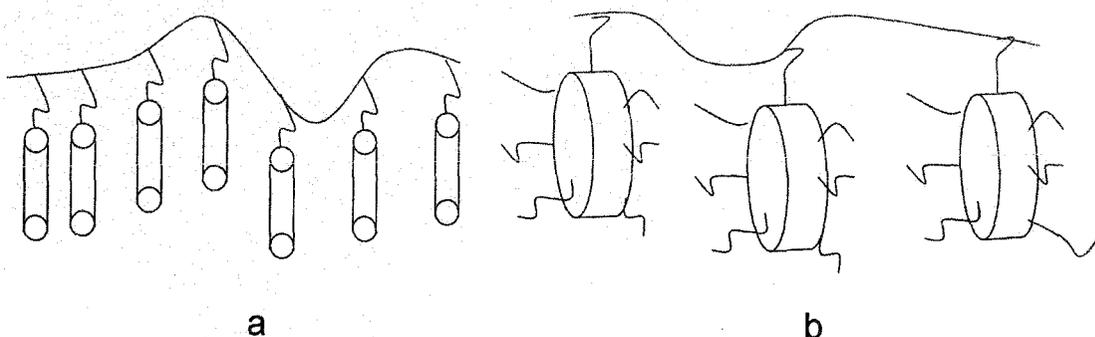


Figure 1.8. Side chain polymer liquid crystal.

1.4. Liquid Crystal Displays (LCDs):

The most common application of liquid crystals is in the field of Liquid Crystal Displays (LCDs). This field has grown into a multi-billion dollar industry and many significant scientific and engineering discoveries have been made. LCDs are electronic visual display or video display that uses the light modulating properties of liquid crystals. These electronically modulated optical devices are made up of any number of segments filled with liquid crystals and arrayed in front of a light source (backlight) or reflector to produce images in color or monochrome [100-102]. LCDs offer several advantages over traditional Cathode Ray Tubes (CRTs) that make them ideal for many applications. They are more energy efficient and can be disposed of more safely than CRTs. Another important parameter of LCDs is low power consumption. The currently manufactured LCDs consume between 1 and 300 microwatts per square centimeter [103], which is the lowest power consumption of any display type now available. Its low electrical power consumption enables it to be used in battery-powered electronic equipment.

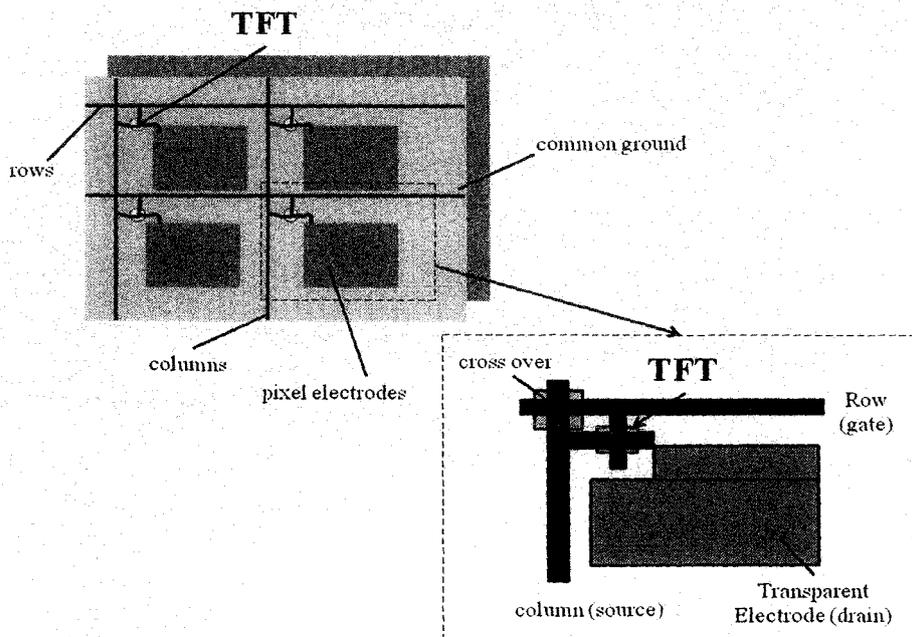


Figure 1.9. Thin film transistors or active matrix displays.

Recent advances in technology have improved the quality of the display and reduced the cost of production to such an extent that flat panel LCDs are now used in mobile telephones, portable notebook computers or flat desktop monitors, as well as commercial TV sets. There are two types of commercially available LCDs-Active Matrix Liquid Crystal Displays (AMLCDs) and Passive Matrix Liquid Crystal Displays (PMLCDs). An active matrix display is built of a matrix type arrangement of rectangular sub-millimeter sized elements (pixels). Each matrix point (pixel that is formed on an amorphous silicon back plate) can be addressed individually by an active electric switching element. The active element is a diode (MIM: metal-insulator-metal) or a transistor (TFT: thin film transistor) (Figure 1.9) [104-106].

In passive matrix LCD's, all the pixels are driven only column -wise and row-wise not using electronic switching device associated directly to one pixel [107]. This type of display is called passive-matrix addressed, because the pixel must retain its state between refreshes without the benefit of a steady electrical charge. As the number of pixels (and, correspondingly, columns and rows) increases, this type of display becomes less feasible (Figure 1.10).

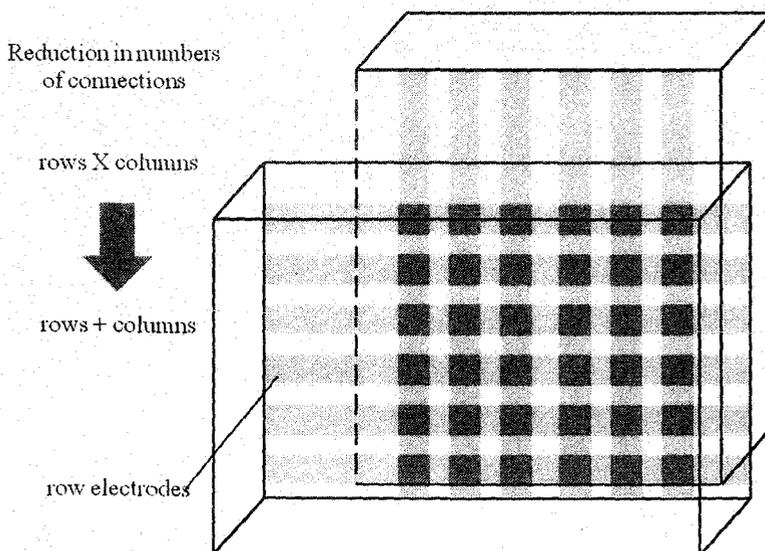


Figure 1.10. Passive matrix displays

The novel Active Matrix configured LC cells largely dominate over passive matrix LCD's due to their superior optical performance and picture quality, particularly for larger size displays. The majority of liquid crystal displays contain nematic liquid crystals. Most of the new emerging LC display technologies fulfill all the requirements required for modern display devices like small viewing angle dependency [108] and fast switching times [109]. There are also many hybrid systems that use LCD technology [110].

1.5. Electro Optic (EO) effect in LCDs:

The optical state of a liquid crystal cell can be controlled by the application of an electric or magnetic field or by changing the temperature. The optical characteristics of the liquid crystal cell changes due to the re-orientation of the molecules resulting in absorption, reflection or scattering of light. This phenomenon of induced optical modulation due to electric or magnetic fields or by temperature is termed as electro-optic or magneto-optic or thermo-optic effects [111, 112] of the liquid crystals respectively. Almost all commercial displays are based on Electro-Optic (EO) effect. The basis of the visible Electro-Optical (EO) effect utilized in LCDs is the birefringence (Δn), which is defined as the difference between the extraordinary refractive index (for light polarized parallel to the director) and the ordinary refractive index (for light polarized perpendicular to the director) (Figure 1.11). Upon switching, the re-orientation of the LC molecules leads to an effective change in the optical path which is defined as $d\Delta n$ (d is the cell gap). This results in a change in the transmission of the display between 0 and 100% [113].

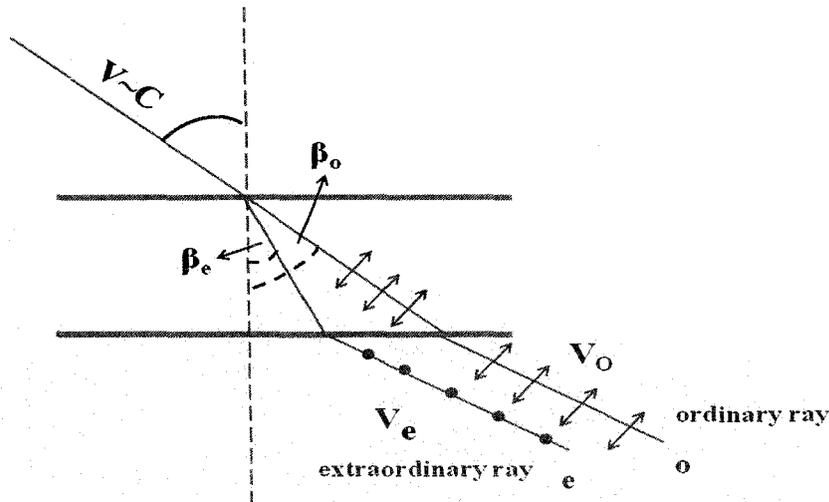


Figure 1.11. Schematic presentation of $\Delta n = n_e - n_o$, v_o = velocity of the ordinary ray and v_e = velocity of the extraordinary ray, β_o = angle of refraction for the ordinary ray and β_e = angle of refraction for the extraordinary ray.

LCDs are generally classified as reflective, transmissive and trans-reflective types. In the reflective type, ambient light is used to illuminate the display. This is achieved by combining a reflector with the rear polarizer. It works best in an outdoor or well-lighted environment in positive contrast mode. Transmissive LCDs have a transparent rear polarizer and do not reflect ambient light. Hence, transmissive LCDs require a backlight to be visible. They work best in negative contrast mode and low light conditions with the backlight on continuously. Trans-reflective LCDs is a mixture of the reflective and transmissive types, with the rear polarizer having partial reflectivity. Here, backlight is provided for use in all types of lighting conditions. The backlight can be left off where there is sufficient outside lighting. This helps in conserving power. In darker environments, the backlight is turned on to provide a bright display. Trans-reflective LCDs works well even when operated in direct sunlight.

1.6. Classification of different electro-optic effects.

Most of the LCDs produced today use either the twisted nematic [TN] [114-117] or the super twisted [STN] [118, 119] electro optic effect. While in



the TN cell the liquid crystal molecules undergo a 90° twist, in Super Twisted Nematic LCDs has a twist of over 180° , typically between 210° and 270° . This shows a much smaller voltage switching range with good contrast ratio and a better viewing angle. Recently, in Cellulose Nanocrystal Electro-optic Devices (CNXL), LC polymer moves in response to an electric field. The CNXL electro-optic effect not only allows for the precise design of various devices, but will perhaps also open the door to exploiting this effect of anisotropic nanoparticles in other areas and utilizing other materials [120-123]. Polymer Dispersed Liquid Crystals (PDLC) composite films constitute a novel class of optical materials. They usually consist of micro-sized liquid crystals (LCs) droplets dispersed in optically transparent polymer matrix [124-128]. These materials have been the subject of much interest due to their wide applications ranging from switchable windows to large area LCD devices. Surface Stabilized Ferroelectric Liquid Crystal (SSFLC) exhibits a fast response, wide view angle and bistable memory capability and has been considered for light shutter and display applications [129]. For some applications bistability of electro-optical effects is highly advantageous, since the optical response (visual information) is maintained even after removal of the electrical activation, thus saving battery charge [130-132]. Liquid Crystal on Silicon (LCoS) projectors have several key advantages over the more popular technologies [11, 133]. A main feature of LCoS is visible pixelation analog-like response. They are capable of delivering rich, well saturated colors. However, every electro-optic effect has limitations the search for new effects that require new LC materials is an ongoing research and development process.

Of the several electro optical effects that are used in LCDs, since this dissertation is mainly concerned with the development of liquid crystalline materials for application in Vertically Aligned mode LCDs [134-148], only the TN mode, VA mode and IPS mode [149-158] as well as their advantages and

disadvantages *vis-a-vis* their applicability in displays have been broadly discussed below.

1.6.1. Twisted Nematic Liquid Crystal Display (TN-LCD):

The conventional flat panel Liquid Crystal Displays (wristwatches or desk calculators) generally use the Twisted Nematic (TN) [114-117] or the Super Twisted Nematic (STN) electro-optic effect [118, 119]. In a TN cell, a nematic liquid crystal is introduced between two substrates with the alignment preparation perpendicular to each other. When the applied voltage is zero, the local optic axis (director) undergoes a continuous 90° twist in the region between the substrates. Therefore the linearly polarized light from the upper polarizer propagating parallel to the helical axis follows the twist of the phase, and as a result, the polarization of the light also turns by 90° (Figure 1.12). This linearly polarized and rotated light emerges through a second polarizer, which is oriented at 90° to the incident one. This light therefore produces a white image on the display and the TN mode is therefore driven in the normally white mode (i.e. the switching off state is white).

When a small voltage (3-5 volt) is applied to the TN-LCDs, the twisted structure is disrupted and the alignment becomes almost perpendicular to the substrates. The polarized light entering the cell now passes through the LC layer without being rotated. Since there is no rotation, the second polarizer blocks the light, producing a black image on the display. The problem with the TN-LCDs is that even when the full voltage is applied, the LC molecules are not completely perpendicular due to strong anchoring between the alignment layers and the liquid crystals. Therefore, the black is not perfectly black, thereby affecting the quality of the black state which is decisive for the contrast of the device. Furthermore, when an intermediate voltage is applied, the various polar alignments of LC molecules in each cell produce different images from different viewing angles. That is, viewers looking at the display from other than directly in front do not see a clear and correct image. Thus, a TN-

mode liquid crystal display device has the inherent drawback in realizing a high contrast representation of images as well as narrow viewing angle. Additionally, they contain a smaller number of matrix segments (eg. 8 x 8) and therefore cannot be applied for displays with high information content. Further development of the TN cell resulted in Thin Film Transistor (TFT) LCDs [159]. This technology enables active switching of a large number of segments (e.g. 640 x 1024) by integrated TFTs. As a consequence of the continuous development of materials and electronics, the performance and the size of TFT LCDs have dramatically improved and due to their excellent resolution quality, they are now a-days utilized in laptops, desktop monitors and televisions.

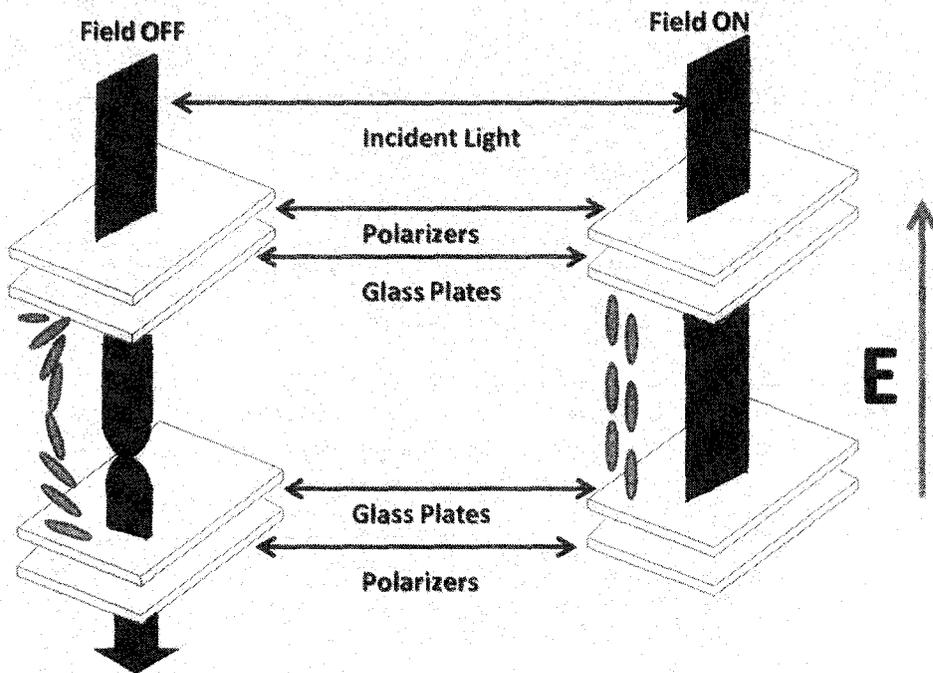


Figure 1.12. Operating principle of the Twisted Nematic (TN) mode.

In spite of all these developments, the problem of narrow viewing angle, slow response times and insufficient contrast ratio of the LCDs, however, still exists. Various techniques have been suggested to improve these problems such as addition of birefringence films [160], the domain-divided twisted nematic (TN) mode [161], the In Plane Switching mode (IPS) [149-158] and

the Vertically Aligned (VA) [134-148] mode. Among these, the VA and IPS switching modes show improved wide-viewing angle and screen update time and are the most promising EO effects for uses in large LC-TV screens with features of high image quality of moving pictures. Computer monitors using these techniques have already started to replace CRT monitors to a large extent.

In IPS cell, though the specific resistance of the liquid crystal mixture is smaller than that of the TN cell, it still provides sufficient Voltage Holding Ratio (VHR) [162] to the pixel. Although IPS mode shows wide viewing angle, the cell gap margin is narrower and response time is rather slower in comparison to the TN mode. Furthermore, the IPS mode exhibits slight colour shift in oblique viewing angle. VA technology on the other hand can produce a display which has ultra wide viewing angle (140°), high contrast, high brightness and a response time of about 25 ms, shorter than both IPS and TN LCD's but still not sufficiently fast for video displays. A recent report shows that the VA mode display consumes less power than IPS.

1.6.2. Vertically Aligned mode Liquid Crystal Display (VA-LCD):

The VA mode is one of the best approaches that are currently being used in Liquid Crystal Display devices. For VA-LCDs, the switching behaviour requires liquid crystal materials with negative dielectric anisotropy ($\Delta\epsilon < 0$) [163]. Liquid Crystal (LC) molecules with lateral polar groups fulfill this requirement. In a Vertically Aligned mode Liquid Crystal Display (VA-LCD), the longitudinal axis of the LC molecules are aligned perpendicular to the upper and the lower substrates of the display in the absence of electric field. With this homeotropic orientation and crossed polarisers, (Figure 1.13) the VA mode is working in the normally black mode [164-168].

With no voltage, all the LC molecules, including those at the boundaries with the substrates, are completely perpendicular. In this state the polarized light passes through the cell without interruption from the LC molecules and is blocked by the front polarizer. Since the blockage is complete, the quality of black produced in this way is excellent and the viewer sees this black from all viewing angles. When a voltage is applied, the molecules shift to a horizontal position. The polarization of the linearly polarized light therefore changes in the liquid crystal layer. Accordingly, when light reaches the analyzer, the light has a polarization component parallel to the polarization axis of the analyzer, and thus the light out of the analyzer is visible to users (Figure 1.13).

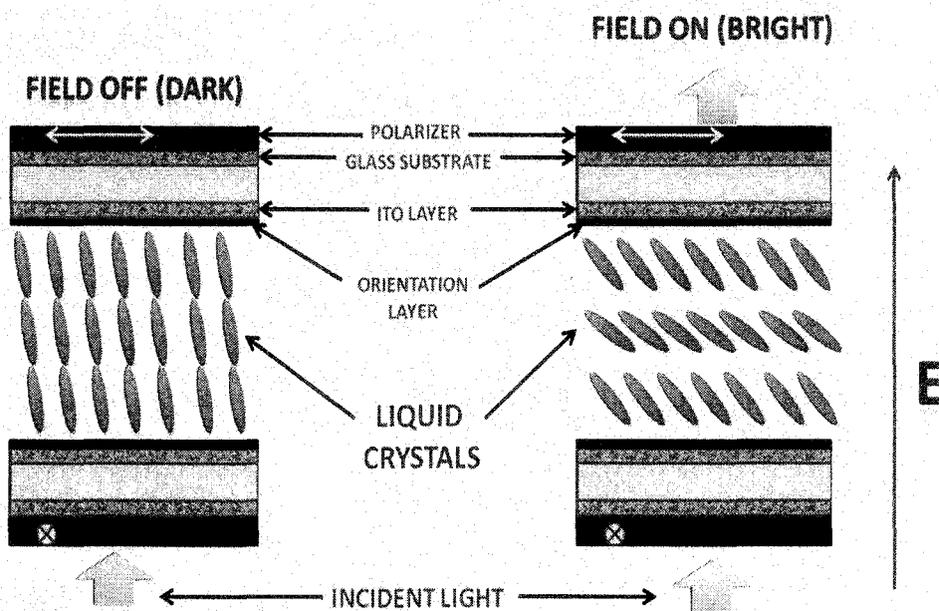


Figure 1.13. Operating principle of the Vertically Aligned (VA) mode.

Furthermore, the pixel and electrode design of VA displays allow for a high aperture ratio (i.e. the fraction of transparent pixel area) resulting in a high brightness of the display. These two points are the main reason for the good contrast of the VA-LCDs.

One of the difficulties of this technique is the switching – on mechanism where the driving electric field tilts the directors randomly in any direction in

the ON state, leading to disclination lines between domains of equal orientations thus deteriorating the optical performance. Multi Domain Vertical Alignment (MVA) TFT LCDs [169, 170] has been recently developed, where each of the multiple domains within each pixel cell channel light at an angle to the substrates, instead of at right angles to it, resulting in all-round increase in viewing angle upto 160° in all directions with a contrast ratio of around 300:1. Another very successful approach is the Patterned Vertical Alignment mode (PVA) [169] where Chevron-shaped patterned electrodes produce a fringe electric field with the in-plane component that directs the molecular tilt in the ON state. The resulting multifold symmetry of the director field gives excellent viewing angle performance, high transmittance and contrast ratio.

One more important aspect of the VA mode display is its switching time. This system can achieve faster response times because there is no twisted structure as in the TN mode and the molecules simply switch between the vertical and horizontal alignments. The first generation of VA-LCDs has already achieved fast switching times of around 25 ms. The gray-scale switching of VA-LCDs however are relatively slow. Recently, this has been significantly improved by the over-driving technique [170].

Thus the VA mode is a very promising technology because of the combination of intrinsically good contrast values and fast switching times.

1.6.3. In Plane Switching (IPS) mode Liquid Crystal Display (IPS-LCD):

In Plane Switching (IPS) [149-158], a general class of operating modes and designs (including such trade names as Advanced IPS or Super-Advanced IPS) is fairly easy to understand, both in terms of how it works and the advantages it provides. Rather than the helical or spiral staircase arrangement of molecules used in a TN LCD, an IPS type starts out in the off state with all LC molecules aligned horizontally and pointing in the same direction (Figure 1.16).

If an electric field is applied horizontally (parallel to the planes in which the molecules lie), but at a 90-degree angle to their long axes, the molecules will tend to rotate to align with the field, except for those lying next to the glass substrate, where the forces that align them with the rubbing layer are strongest (Figure 1.14). This again establishes a helical structure, capable of rotating the polarization of light passing through from bottom to top.

Once again, we have a structure that can be switched on and off by applying a voltage to the proper electrodes. When on, the polarization rotation will permit light to pass through the cell; when off, light cannot get through the crossed upper and lower polarizer. However, this mode of operation in which

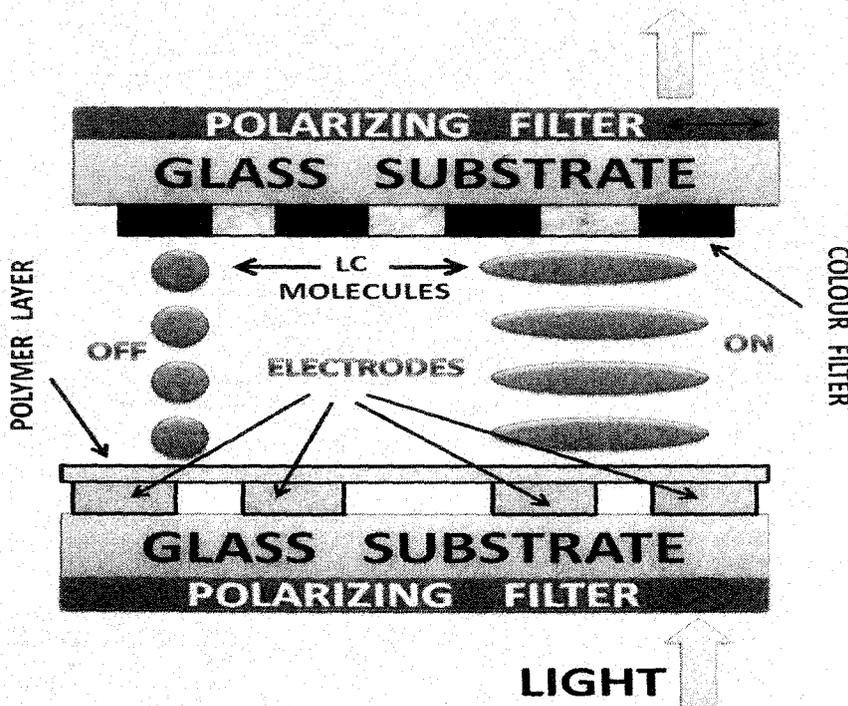


Figure 1.14. Schematic diagram of In Plane Switching (IPS) Displays.

all the molecules always lie in a given plane, exhibits little or no change in the display's appearance when viewed off-axis. IPS displays have an inherently wider viewing angle (up to 160 degrees or greater) than the original TN designs.

A disadvantage of the inter-digital electrodes is the limitation of the aperture ratio resulting in lower brightness. Thus, one of the most challenging

points is to achieve high brightness in combination with good contrast. A feasible method to increase the aperture ratio is to increase the distance between the inter-digital electrodes. But this gives rise to an increase of the driving voltage. The compensation requires higher dielectric anisotropy of LC materials, which normally leads to higher rotational viscosities, which in turn might deteriorate the switching times.

1.6.4. Liquid Crystal on Silicon (LCoS) Technology:

LCoS is a hybrid between Liquid Crystal Display (LCD) and Direct Light Projector (DLP). LCD uses liquid crystals, one for each pixel, on glass panels. Light passes through these LCD panels on the way to the lens and is modulated by the liquid crystals as it passes. Thus it is a "transmissive" technology [11, 133]. On the other hand, DLP uses tiny mirrors, one for each pixel, to reflect light. DLP modulates the image by tilting the mirrors either into or away from the lens path. It is therefore a "reflective" technology. LCoS combines these two ideas. It is a reflective technology that uses liquid crystals instead of individual mirrors. In LCoS, liquid crystals are applied to a reflective mirror substrate. As the liquid crystals open and close, the light is either reflected from the mirror below, or blocked. This modulates the light and creates the image.

LCoS projectors have several key advantages over the more popular technologies. First, due partly to inherent high resolution and partly to high fill factors (minimal space between pixels) on the chips, visible pixelation on an LCoS machine is nonexistent. The pixel structure of LCoS is 1280x720 DLP Mustang chip with excellent high resolution. So the resulting video image can be smooth as silk. Moreover, with LCoS the pixel edges tend to be smoother compared to the sharp edges of the micro-mirrors in DLP. This gives them an analog-like response. In practical terms, this gives the LCoS image a smoother,

more natural look and feel, while DLP tends to impart a synthetic sharpness to the image that some would describe as harsh.

1.7. Advantages of Vertically Aligned mode Liquid Crystal Displays over other display devices:

One of the initial attractive features of the VAN mode is that it has an inherent high contrast, virtually independent of wavelength or cell gap. This is due to the almost vertical orientation of the liquid crystal molecules in the black state, which keeps residual birefringence to a minimum and results in a contrast ratio that is close to the contrast ratio of the crossed polarizers themselves.

These are the main characteristics of a VAN display:

- (a)** Very compact and light.
- (b)** Low power consumption.
- (c)** Very little heat emitted during operation, due to low power consumption.
- (d)** No geometric distortion.
- (e)** The possible ability to have little or no flicker depending on backlight technology.
- (f)** Usually no refresh-rate flicker, because the LCD pixels hold their state between refreshes (which are usually done at 200 Hz or faster, regardless of the input refresh rate).
- (g)** Very thin compared to a CRT monitor, which allows the monitor to be placed farther back from the user, reducing close-focusing related eye-strain.
- (h)** Razor sharp image with no bleeding/smearing when operated at native resolution.
- (i)** Emits much less undesirable electromagnetic radiation than any other monitor (in the extremely low frequency range).
- (j)** Can be made in almost any size or shape.
- (k)** No theoretical resolution limit.

- (l)** Can be made to large sizes (more than 24 inches) lightly and relatively inexpensively.
- (m)** Electromagnetic emissions are absent in LCDs.
- (n)** Image geometry is uniform in LCD while the same is distorted in case of a CRT monitor.
- (o)** Eye fixation times are 9% shorter in LCDs and 15% fewer eye fixations are needed to read the same information from an LCD if compared with a CRT.
- (p)** Visual search error frequency is 22% less when reading from an LCD than a CRT.
- (q)** Visual search times for text targets embedded in a screen of text are 22% faster for LCDs than CRTs, and also faster for low contrast, small characters.
- (r)** In an LCD the backlight aging is independent of image content.

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