Active Matrix

Flat Panel Displays

Part 1. LCD (1)

Introduction

The currently dominant flat panel display (FPD) technology is based upon the use of liquid crystal materials to produce active matrix liquid crystal displays (AMLCDs).

Other display effects, which are now appearing in commercial products, are electrophoretic displays (EPDs) in e-readers, and organic light emitting diodes (OLEDs) in some small diagonal, portable displays.

→ This chapter deals with the operation and addressing of active matrix flat panel displays, AMFPDs, and will primarily focus on liquid crystal displays.

The active matrix LCD is currently the most commercially significant display technology, offering products across the size ranging from ~1'' portable displays through to 100'' TVs, as illustrated in Fig. 4.1.

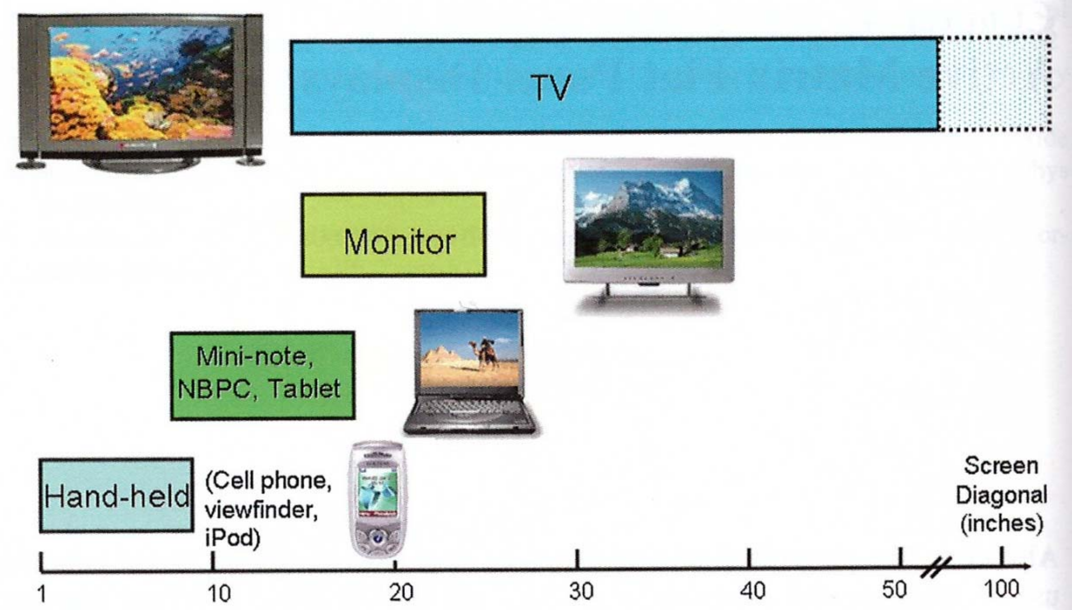


Fig. 4.1 AMLCD product applications grouped by display diagonal (the *dotted box* for LCTV illustrates the larger diagonal TVs demonstrated at electronics shows)

The annual revenue of AMLCD industry in 2011: ~$B86 (~97조 596억원) with a long-term annual growth rate of ~10%

↓

85%: larger diagonal displays (notebook, monitor and TV)

15%: small and medium diagonal display (cell phone, portable media players, net-books and tablets)

The growth of AMLCD industry has been facilitated by the manufacturability of high quality thin film transistors (TFTs) for display addressing, and, equally, the development of the industry has stimulated the world-wide interest and research into TFTs.

→ Among the different TFT technologies, amorphous Si TFTs dominate the current product range, although poly-Si TFTs are found in some of the small and medium-sized products.

Also, within this latter size range, two other display technologies are emerging, in particular, EPDs, and OLEDs.

→ The EPDs are reflective displays, with low power consumption, and are of particular relevance to e-reader devices. The current addressing devices are primarily a-Si TFTs, although the e-reader has also been identified as an appropriate vehicle for flexible displays, and for the use of organic addressing TFTs.

→ The OLED displays demand a higher drive current than LCDs, and the current manufacture of AMOLEDs, for products like cell-phones, has focused on the use poly-Si TFTs for the addressing transistors.

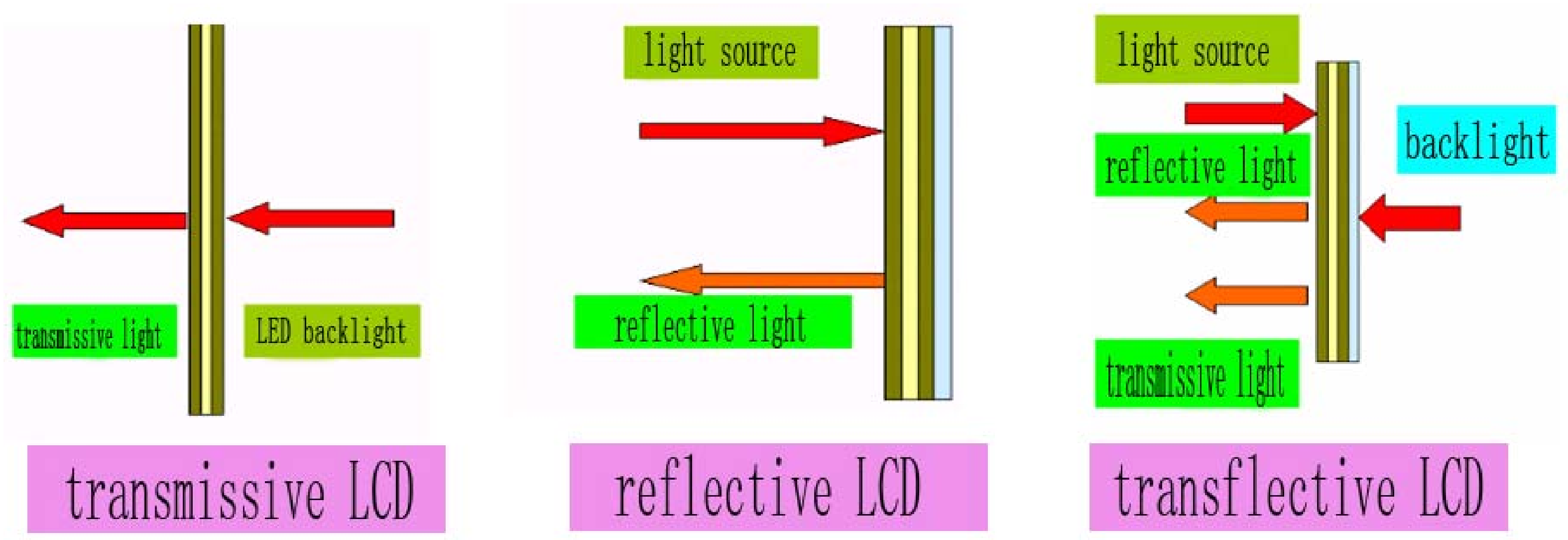
→ There has also been strong research interest in using amorphous oxide TFTs (such as In-Ga-Zn-O), rather than poly-Si TFTs, for addressing large diagonal AMOLEDs.

The motivation here has been the recognition that AMOLED displays are more sensitive to TFT drive current non-uniformities than AMLCDs, and the amorphous nature of the oxide TFTs is perceived as offering better uniformity than the laser crystallized poly-Si TFTs.

Liquid crystal displays can operate in either the transmissive mode (illuminated by a back-light), or the reflective mode (relying upon the reflection of ambient light), or the transflective mode (mixture of the other two).

→ The transmissive mode is used in the majority of applications (e.g., notebook, monitors and TVs), whereas the other modes are more frequently employed in smaller portable displays, where power consumption and battery life are important issues.

→ The discussion in this chapter is limited to the more wide-spread transmissive mode.



Liquid Crystal Cells

- LC Material

A liquid crystal (LC) material is one in which there is a temperature dependent phase, which exhibits the structural organization of a crystal, and the viscosity of a liquid.

→ The former property results in an anisotropic refractive index and birefringence, and the latter enables the material to rapidly respond to an external influence, such as a change in an applied field.

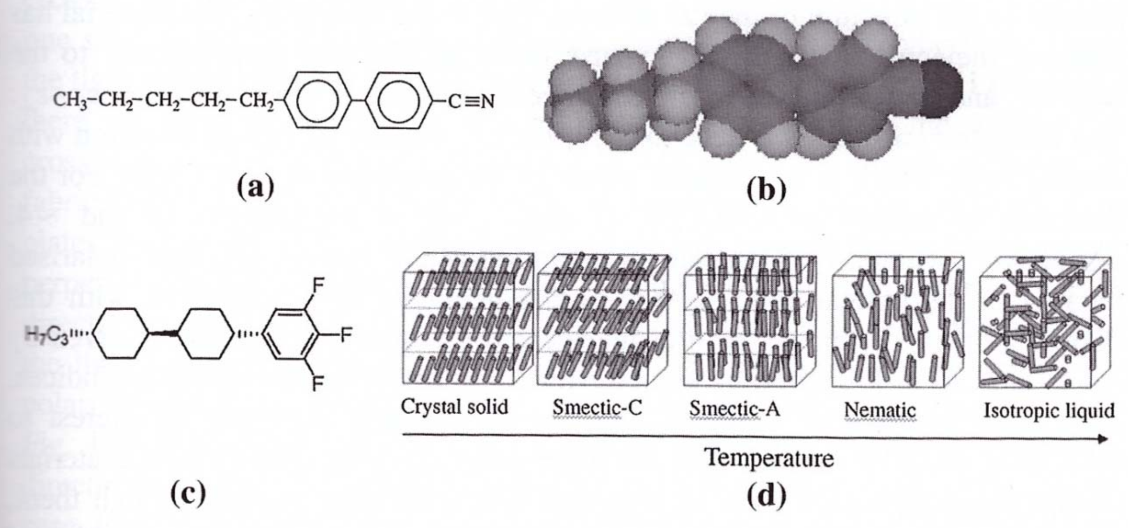


Fig. 4.2 **a** 4′-n-pentyl-4-cyano-biphenyl (5CB) LC molecule, **b** space filling model of 5CB, **c** 1,2,3 trifluorobenzene derivative molecule developed for TNLCs, and **d** temperature dependent phases of rod-like LC molecules (**a**, **b** and **d** Reproduced from [9] with permission of John Wiley & Sons, Inc, and **c** Reprinted from [10] with permission of SID)

LC materials come in a variety of forms and phases, and the type of specific interest for AMLCDs is composed of long-chain molecules.

(e.g., aspect ratio of ~4: length ~2 nm & diameter 0.5 nm)

Between two phase extremes (isotropic liquid & crystalline solid), intermediate liquid crystal phases are shown, with the nematic phase being the highest temperature one, and the clearing point of the material is defined as the temperature at which the isotropic liquid forms.

→ In the nematic phase, the molecules have orientational order, but no positional order. In other words, the long axis of the molecules is aligned predominantly in the same direction, which is called the liquid crystal director, but there is no further ordering within this direction.

→ At a lower temp., the smectic-A phase can arise, where the orientational ordering of the nematic phase is preserved, but there is now some positional ordering of the aligned molecules into layers, although there is no further positional ordering within the layers themselves. (the liquid crystal director is perpendicular to the layers).

→ Some materials display further ordering into the smectic-C phase, in which the director is now at an angle to the layer.

The nematic phase has lower viscosity than the grease-like smectic phases, and is the preferred material for LCDs, although it should be added that the nematic materials are synthesized compounds containing a number of constituent mixtures rather than being a single, simple LC material.

→ Indeed, for a given application, the constituent parts are used to optimize the properties of the material, such as clearing point, speed of response or reduced driving voltages etc.

→ For the practical application of these materials in AMLCDs, the nematic LC phase needs to be stable from ~-40℃ to ~100℃, have high resistivity, fast response times, specific dielectric properties, and excellent chemical stability.

The directional alignment of the LC molecules makes the material dielectrically and optically anisotropic, and, in this case, the optical axis is parallel to the direction of the LC director.

→ Due to the anisotropy, the material has different dielectric constants for electric fields parallel and perpendicular to the director, and the difference in dielectric constants, $\Delta\varepsilon$ is given by $\Delta\varepsilon = \varepsilon_{\parallel} - \varepsilon_{\perp}$.

→ The dielectric anisotropy is necessary for the LC director to change direction with electric field, which is an essential aspect of the operation of the LC cell.

For the material of interest in AMLCDs, $\varepsilon_{\parallel}$ and $\varepsilon_{\perp}$ are of the order ~10 and ~4, respectively.

→ Similarly, there are different refractive indices for light polarized parallel to the optical axis, $n_{\parallel}$ and perpendicular to it, $n_{\perp}$.

Material with this optical property is known as birefringent, and the birefringence, Δn, is given by $\Delta n = n_{\parallel} - n_{\perp}$.

Depending upon the relative sizes of the two refractive indices, Δn can be positive or negative, and, for the nematic materials of interest to AMLCDs, positive Δn materials are more generally used.

Birefringent materials change the polarization state of polarized beams of light passing through them, when the angle of incidence is between 0° and 90° with respect to the direction of the LC director.

This change of polarization is exploited in AMLCDs, using a particular form of nematic cell structure, known as a twisted nematic cell.

▪ Twisted Nematic LC Cell Structure

The structure of a twisted nematic (TN) cell consists of a 4-6 μm thick liquid crystal layer sandwiched between two glass plates.

→ The inner surfaces of the plates are coated with a transparent metal conductor, such as indium tin oxide, ITO, so that an electrical bias can be applied across the liquid crystal.

→ In addition, the outer surface of each ITO layer is coated with an LC alignment layer, such as polyimide, which is textured by rubbing, in order to anchor the rod-like nematic LC molecules to the surface in a predetermined fashion.

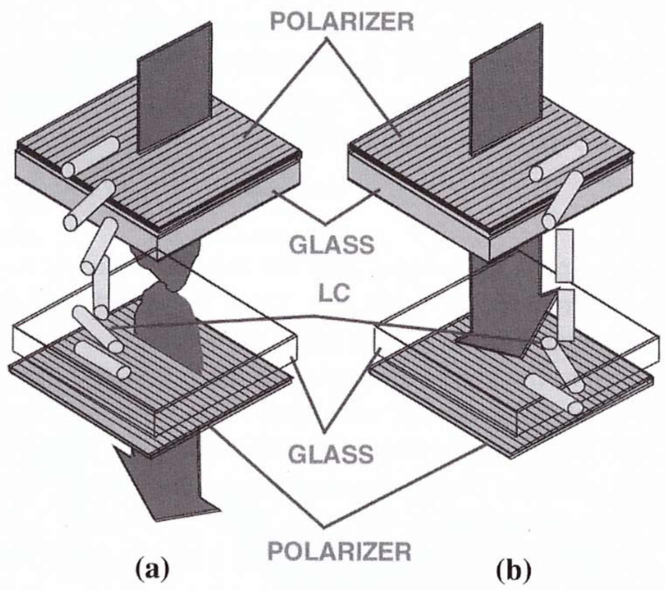


Fig. 4.3 TN LC cell structure (**a**) transmitting state, with zero applied bias across LC, and (**b**) black state, due to LC bias voltage (Reproduced from [9] with permission of John Wiley & Sons, Inc)

→ The outer surfaces of the glass plates are sandwiched between two crossed, linear polarizer plates, and the LC cell is illuminated with white light from one side of the stack, and viewed through the polarizer on the other side.

Hence, the light entering the cell is plane polarized, and, in the absence of the LC material, there would be no optical transmission through the cell due to the action of the crossed polarizer.

However, as shown in Fig. 4.3a, the alignment layers are fabricated so that the LC directors of the molecules in immediate contact with plates are parallel to the polarization directions, but, because the two directions are perpendicular to each other, a 90˚ twist is induced in the orientation of the LC director through the cell.

→ This induces a 90˚rotation in the plane of polarization of the light passing through the cell, so that the light is transmitted by the crossed polarizer on the exiting surface of the cell, and the cell appears bright.

→ Referring to Fig. 4.3b, when a suitable voltage is applied across the liquid crystal, the LC directors line up with the field, and the 90° twist is removed from the LC.

In this case, there is no longer a rotation in the plane of polarization of the light passing through the cell, and the light is not transmitted by the crossed polarizer on the opposite face: the cell now appears dark.

→ When the voltage is reduced back to zero, the LC molecules relax back to the 90° twist shown in Fig. 4.3a, and the speed of this relaxation is a function of the molecular form of the LC and the cell thickness, d.

For a given liquid crystal material, with a birefringence Δn, the required cell thickness, to give the 90° twist to the light in the unbiased state, is determined by the Gooch-Tarry condition:

$$d\Delta n = \lambda \cdot \sqrt{m^2 - 1/4}$$

where m is an integer (the thinnest cell is given by $m = 1$).

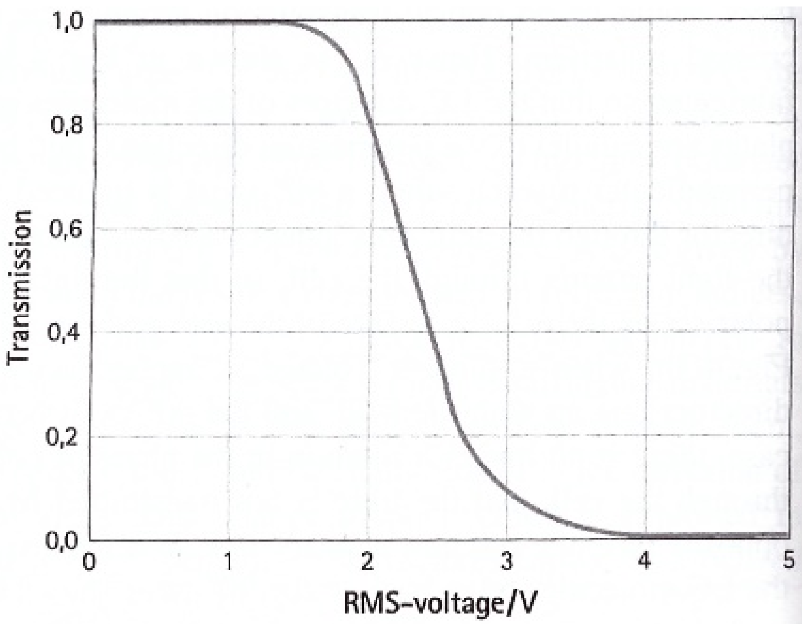
For example, for d ~ 5 μm, the LC material needs to be engineered to have a Δn value of ~0.1 (@ λ= 550 nm)

From the above discussion of the bright and dark states, it is clear that the TN cell acts as a voltage controlled light valve.

Moreover, intermediate voltages determine the particular value of the LC twist between 0° and 90°, and, thereby, control the detailed optical transmission of the cell, as shown by the voltage/transmission curve in Fig. 4.4.

→ A cell having this transmission curve is referred to as normally white (whilst with parallel polarizer, it would be normally black).

Fig. 4.4 Transmission versus voltage curve of normally white TN LC (Reprinted from [12], © Merck KGaA, Darmstadt, Germany)



→ In this transmission curve, the threshold voltage is the minimum voltage required to induce a measurable reduction in bright state transmission, and the saturation voltage is the minimum voltage to achieve the black state. The contrast ratio is given by the ratio of the maximum and minimum transmission values, and would typically be ~250 or more.

→ The transmission curve in Fig. 4.4 is shown only for positive drive voltages, but it is symmetric about y-axis for both negative and positive drive voltages.

In fact, a.c. drive is always used with these LCs to avoid the electro-chemical damage to the material, which would arise from d.c. driving.
(∵ mobile ions in LC materials) → polarity inversion

Given the monochromatic nature of the TN cell, colored displays are achieved by passing the light from the cell through red, green and blue (RGB) colored filters.

→ The cell structure should be regarded as a single pixel, and a display can consist of more than a million pixels, each of which need to be individually addressed to ensure that each has the correct voltage applied to achieve the required optical transmission

→ In principle, this can be achieved with ‘cross-wire’ addressing, in which a matrix of patterned ITO addressing lines are used on one side of the display together with an orthogonal set on the other side of the display, and the combined voltage at any point will determine the optical transparency at that point.

This is known as passive matrix addressing, but is only used in low resolution and low quality displays, because, as the number of pixels increases, the addressing time of each pixel decreases, and the image loses brightness and contrast.

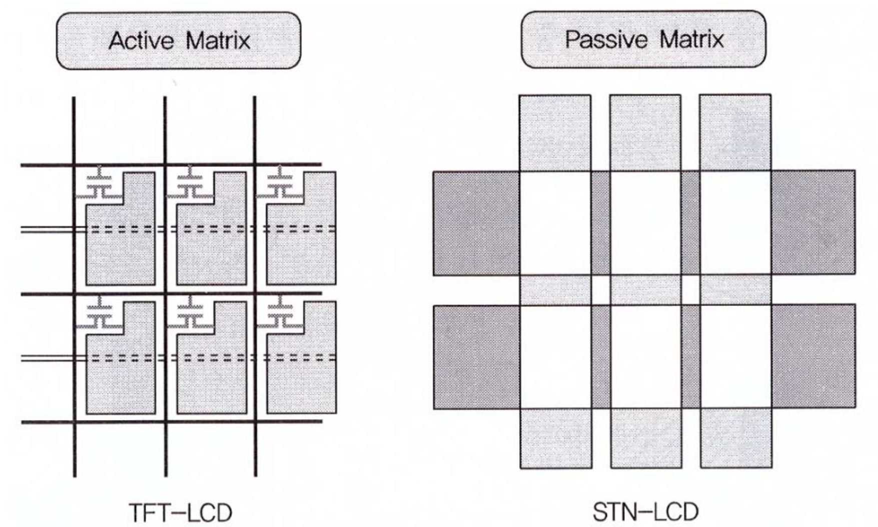


Fig. AM-LCD vs. PM-LCD

→ All present day high quality displays use active matrix addressing, in which there is a transistor in each pixel, as illustrated in Fig. 4.5a.

This schematically shows the definition of the ITO on the bottom plate into a matrix of individual pixel areas, each of which has an addressing transistor.

The ITO on the upper glass plate is unpatterned, and is often referred to as the common electrode.

The color filters are also shown on the top plate, where they have been fabricated in a stripe arrangement (although other arrangements are also possible).

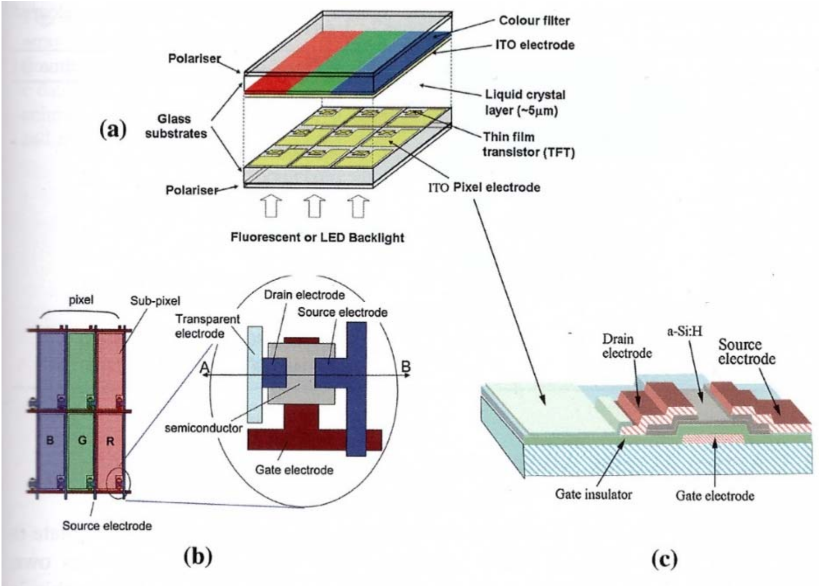


Fig. 4.5 a Illustration of AMLCD cell, b detail of pixel layout, showing TFT, c schematic cross-section of a-Si:H TFT (b and c reprinted with permission from [19])

In fact, each of the three pixels associated with the triad of color filters can be thought of as sub-pixels of the display, which is usually shown in the notation for the number of horizontal pixels in a display as N(×3), where N is related to the resolution of a display. (see Table 4.1)

→ For example, in a colored VGA display, with a resolution of 640 × 480 pixels, there is an array of 640(×3) horizontal pixels and 480 vertical pixels,

→ The transistors in each pixels are used as switching devices to set the voltage across the pixel in a short addressing time, and to store it until the next refresh signal is obtained, as described in the following section.

Table 4.1 Common display formats, listing the number of rows and columns (for coloured displays)

subpixels = # TFTs

Format	# Columns	# Rows	# Pixels	R address time (s)
VGA	640(×3)	480	921,600	3.47E−05
SVGA	800(×3)	600	1,440,000	2.78E−05
XGA	1,024(×3)	768	2,359,296	2.17E−05
WXGA	1,280(×3)	800	3,072,000	2.08E−05
SXGA	1,280(×3)	1024	3,932,160	1.63E−05
UXGA	1,600(×3)	1200	5,760,000	1.39E−05
HDTV	1,920(×3)	1080	6,220,800	1.54E−05
WUXGA	1,920(×3)	1200	6,912,000	1.39E−05
QXGA	2,048(×3)	1536	9,437,184	1.09E−05
QSXGA	2,560(×3)	2048	15,728,640	8.14E−06
QUXGA	3,200(×3)	2400	23,040,000	6.94E−06

Active Matrix Addressing

Active matrix addressing is shown schematically in Fig. 4.5a, in which the plate is patterned into an array of pixels, each one of which is addressed by its own transistor.

→ The most widely used addressing transistor is an a-Si:H TFT: this is shown in the pixel layout in Fig. 4.5b, and in cross-section in Fig. 4.5c

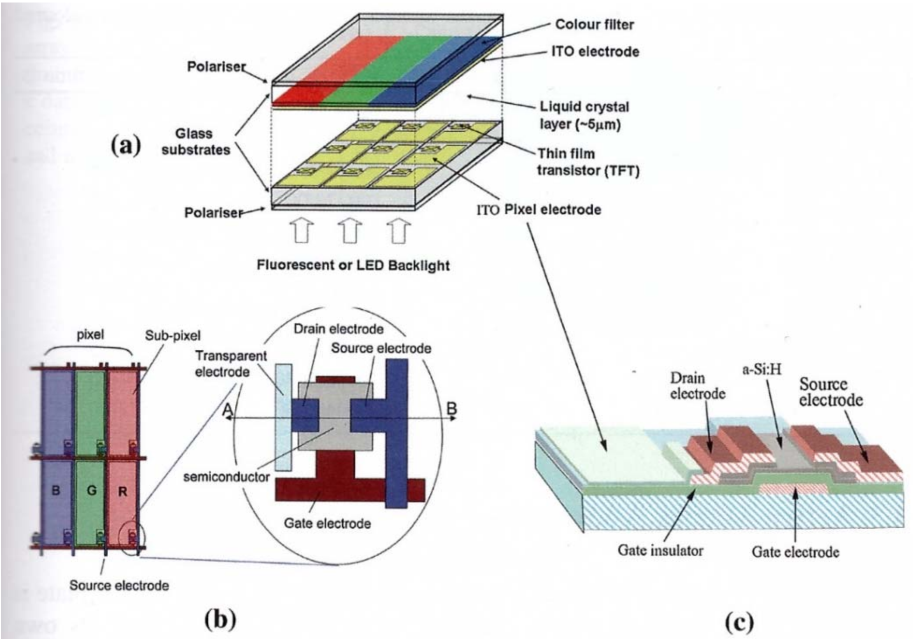


Fig. 4.5 **a** Illustration of AMLCD cell, **b** detail of pixel layout, showing TFT, **c** schematic cross-section of a-Si:H TFT (**b** and **c** reprinted with permission from [19])

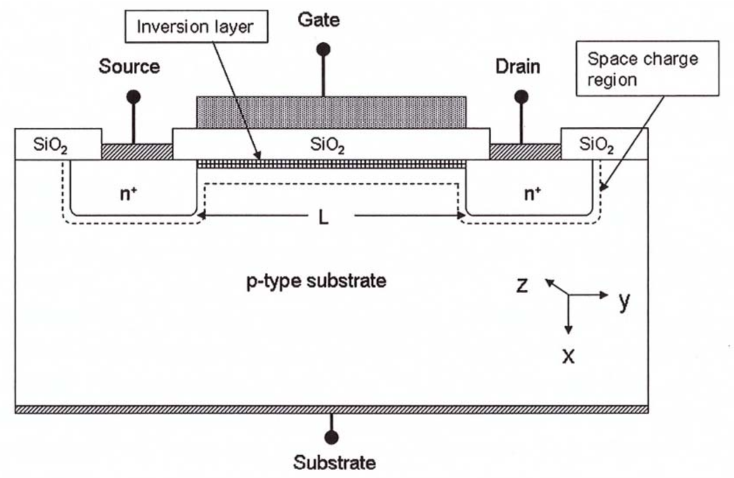


Fig. 3.1 Schematic cross section of a MOSFET, with the gate voltage larger than the threshold voltage, and showing the surface inversion and depletion layers. The channel length is L, and the width, W, is perpendicular to the page

Although this is a field-effect transistor, like the MOSFET discussed previously, its architecture is quite different, being a bottom-gated inverted staggered structure, rather than a top-gated coplanar structure.

Moreover, the source and drain connections are not self-aligned to the gate electrode, but overlap it.

This overlap results in a parasitic capacitance, C_{GD}, between the gate and the drain terminals, which can induce display performance artefacts.

→ In the MOSFET case, the edges of the source and drain regions are coincident with the gate edges, which is the standard MOSFET architecture.

This architecture is referred to as self-aligned, and is achieved by using the gate electrode as a mask for doping the source and drain regions by ion implantation.

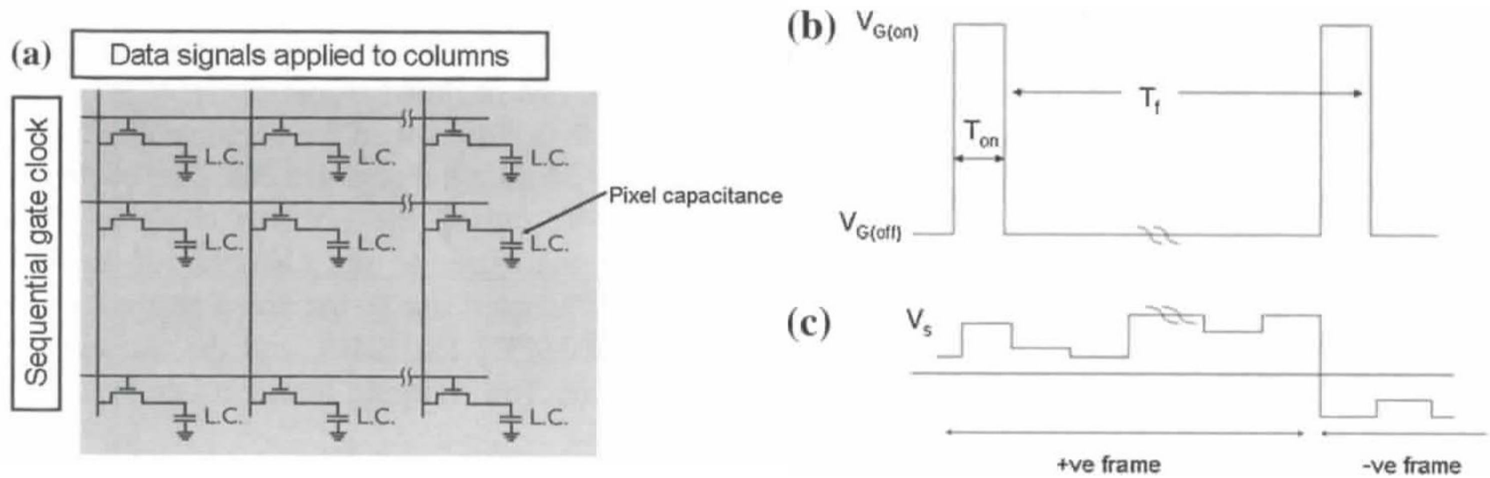
As illustrated in Fig. 4.6a, the matrix of TFTs is connected in rows and columns, with a common connection to the gate electrodes in each row, and a common connection to the source terminals in each column.

→ The row lines carry the TFT addressing signals, and the column lines carry the data signal, V_s.

→ The drain of each TFT is connected to its ITO pixel electrode, and the timing of the row and column voltages are shown in Fig. 4.6b and c, respectively.

→ The high resistivity LC material is represented by a capacitor, which is charged up to the appropriate signal voltage, V_s, through its TFT.

Fig. 4.6 **a** Active matrix array layout, **b** Gate line timing signal for row m, and **c** data signal waveform for column n, showing positive and negative frames



This is achieved by line-at-a-time addressing, during which the data signal is fed into the display in a serial row-by-row process, by sequentially switching on each row ($V_G = V_{G(on)}$), whilst holding the others in the off-state ($V_G = V_{G(off)}$).

→ If the addressing TFTs are made from a-Si:H, they will be n-channel devices, and the row select voltages, $V_{G(on)}$, will be positive, whilst the row de-select voltage, $V_{G(off)}$, will be negative.

→ The timing signals are related to the a.c. mains frequency, such that the display is refreshed every frame time, T_f, which will be 16.7 ms (1/60) for a 60 Hz frame rate.

If there are M rows and N columns in the display, then the time available, T_{on}, to charge the TFTs in a given row is given by T_f/M, and this will be a function of the display format.

Table 4.1 lists the row addressing times, which vary from ~35 to ~7 μs, across the range of display formats.

During this interval, the signal voltages on the column electrodes of the display are applied in parallel to the common sources of the TFTs, but will charge only the one row of LC capacitors connected to the row of TFTs, which has been turned on.

→ The on-current of the TFTs must be large enough to charge the capacitors in the time available.

The maximum charge will be when the voltage is changing from +black to –black, i.e., $+V_{sat}$ to $-V_{sat}$ (or vice versa), and an approximate value of the required current is given by:

$$I_{on} > 5 \times \frac{2V_{sat}C_{LC}}{T_{on}} \rightarrow \text{(for example, } I_{on} \geq 3.6 \times 10^{-7} A \text{ for } C_{LC} = 0.25\, pF\text{)} \quad (1)$$

where C_{LC} is the capacitance of the LC, and the factor 5 is to ensure the full charging of the pixel.

At the end of the row on-time, that row is deselected (by switching the gate bias to a negative value), and the adjacent row is switched on, and the process described above is repeated.

→ Hence, the display information is loaded row by row during a frame time, and, at the end of this period, the whole process is repeated with the next 'field' of information.

→ However, between the loading of the data signals onto a given row of TFTs, and its updating a frame-rate later, it is important that the original signal voltages are maintained across the LC capacitor.

During this interval, the sources of the de-selected TFTs will experience a variety of different voltages, which will be different from the voltage, V_{LC}, on the drain terminal, and, depending upon the TFT leakage current, this potential difference acts as a driving force to reset the voltage on the drain.

To ensure that this effect is minimized, the maximum tolerable leakage current, I_{off}, is constrained to be below a certain maximum value, to give, for instance, less than 1% discharge of the pixel voltage, so that:

$2V_{sat}$

$$I_{off} < 10^{-2} \times \frac{C_{LC}\Delta V_{max}}{T_f} \rightarrow \text{(for example, } I_{off} \leq 4.5 \times 10^{-13} A \text{ for } C_{LC} = 0.25\, pF\text{)} \quad (2)$$

→ Hence, with line-at-a-time addressing, the TFT is acting as a high quality switch, with a minimum on:off current ratio given by Eqs. (1) and (2)

$$\frac{I_{on}}{I_{off}} > 500M > 5 \times 10^5 \text{ for a display with ~1000 rows}$$

rows

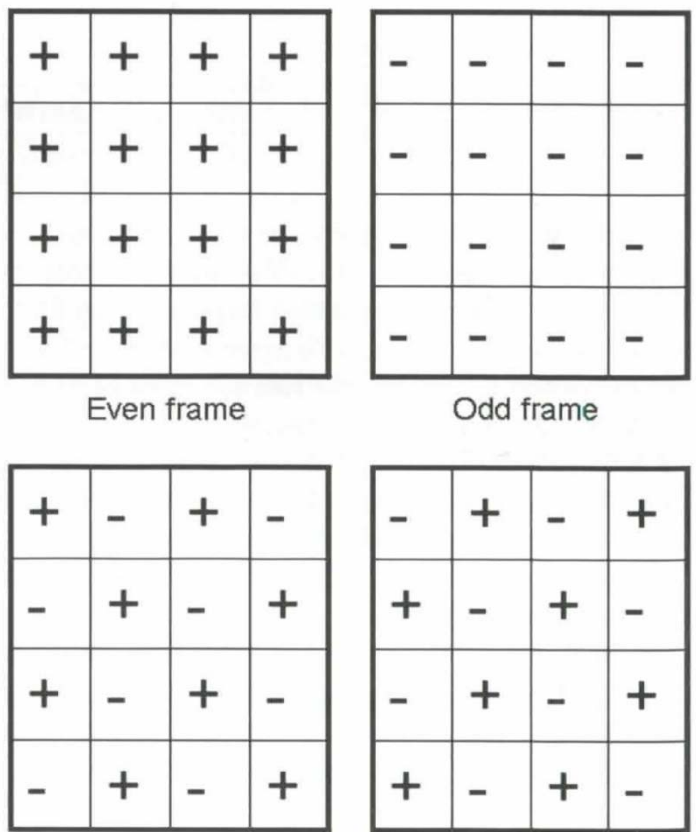
The other potential leakage current path is through the LC itself, but its resistivity is typically ~$1 \times 10^{12} \Omega \cdot cm$, and, although this is not negligible, the associated leakage will be less than the TFT leakage.

The polarity of the signal voltages is changed in a uniform fashion across the whole field between frames. (polarity inversion)

→ This is illustrated in Fig. 4.8a, and is known as frame inversion.

From a display performance point of view, this has well documented drawbacks, such as increased flicker, and increased vertical cross-talk.

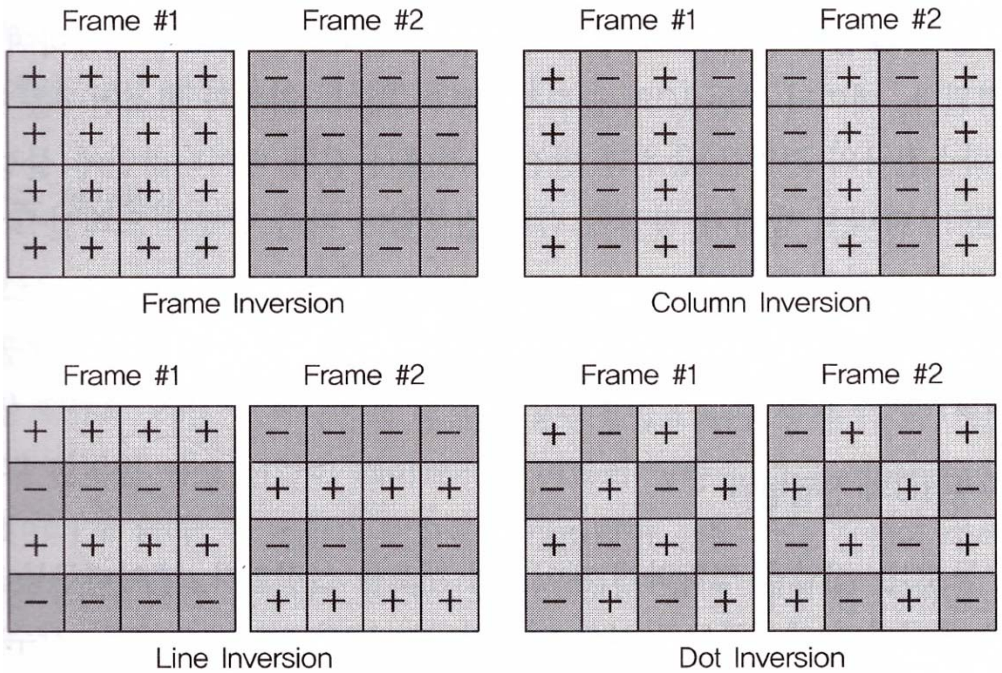
Fig. 4.8 AMLCD data signal drive inversion schemes, showing the signal polarity in consecutive frames with (**a**) frame inversion, and (**b**) dot inversion



→ In fact, there are several alternative inversion schemes, such as row inversion (the polarity of each row of data alternates within one frame), or column inversion (the polarity of each column of data alternates within one frame), or dot inversion.

Dot inversion is a mixture of row and column inversion, in which the polarity of every other pixel alternates, and gives the lowest value of cross-talk and flicker.

In all these schemes, the polarity pattern within one frame is reversed in the next frame, so that each LC pixel experiences alternating +ve and –ve biases.



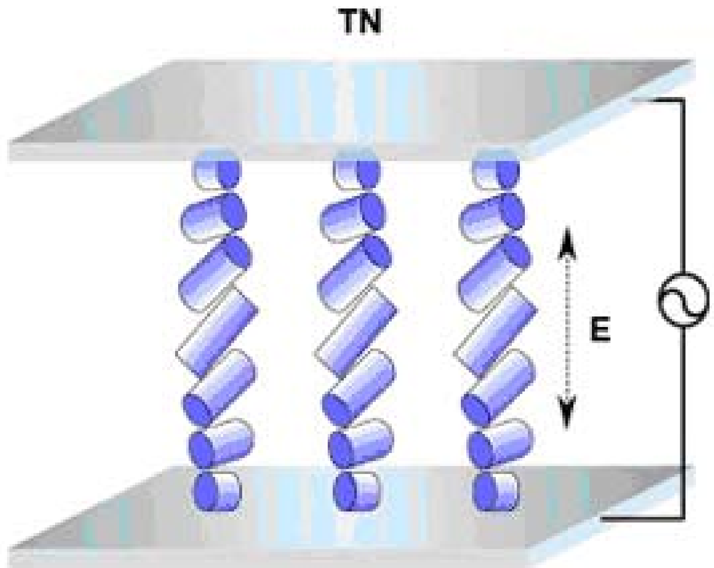
The foregoing description of active matrix addressing of LCDs is somewhat simplified and idealized, and there are important behavioral artefacts associated with parasitic capacitances within the pixel, such as cross-talk and pixel off-set voltage (=kick-back voltage).

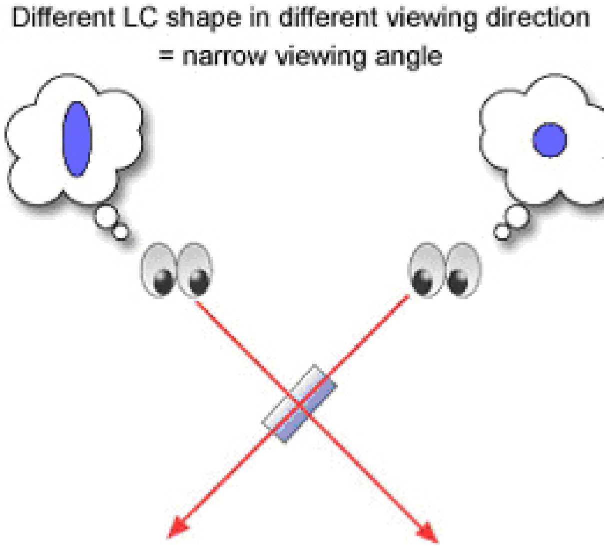
→ The magnitude of these effects is determined by the detailed pixel layout, and these effects will be discussed next.

It should also be mentioned that additional capacitance is frequently introduced in parallel with the pixel capacitance, by means of a storage capacitor.

Finally, the viewing angle dependence of brightness and contrast in the simple TN cell is limited, and, although it is acceptable in smaller displays up to notebook size, it was necessary to improve it in the larger monitor and TV displays.

→ In this TN cell, at mid-grey levels, the LC director is changing direction from horizontal towards vertical in the middle of the cell, and, at different viewing angles, this variable direction changes the transmittance of the cell.





To improve the viewing angle, modified cell architecture have been developed, of which the two most widely used are the in-plane switching (IPS), and the multi-domain vertical alignment mode (VA).

→ The operation of the IPS cell, with crossed polarizers, is shown in the off and on states in Fig. 4.9a and b, respectively.

In both cases, the LC director is parallel to the plane of the glass plates (and in Fig. 4.9a, the director is perpendicular to the page).

The major difference from the simple TN cell, is that the switching electrodes are on the TFT plate, so that, when a bias is applied between these electrodes, the molecules rotate about their short axis, and the director aligns with the field.

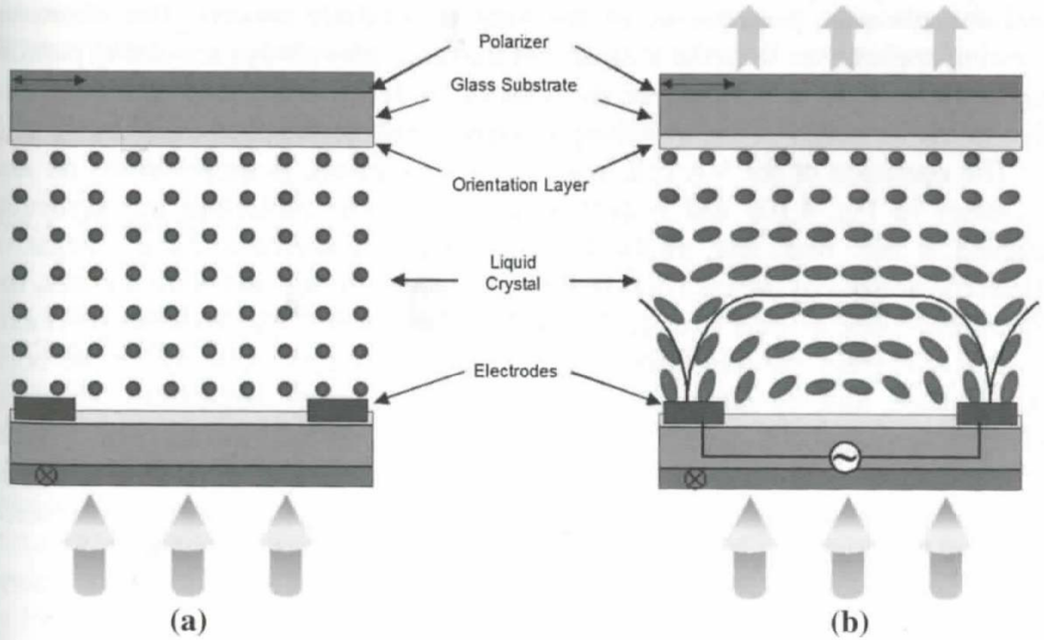


Fig. 4.9 Illustration of the normally black, IPS mode of LC cell switching. **a** Zero bias dark-state. **b** Biased bright-state (Reprinted from [10] with permission of SID)

This puts a twist into the column of liquid crystal molecules, and the plane of polarization of the light is similarly rotated.

The improved viewing angle arises from the long axis of the molecules always remaining parallel to the plane of the cell.

However, the trade-off with IPS is a reduced aperture ratio due to the inclusion of the switching electrodes within the pixel.

→ The operation of the VA cell, with crossed polarizers, is shown in the off and on-states in Fig. 4.10a and b, respectively.

The molecules are vertically aligned at zero bias, and, as the LC mixture is engineered to have a negative dielectric anisotropy, when a bias is applied between the top and bottom plates, the molecules rotate in order to align their short axis with the field.

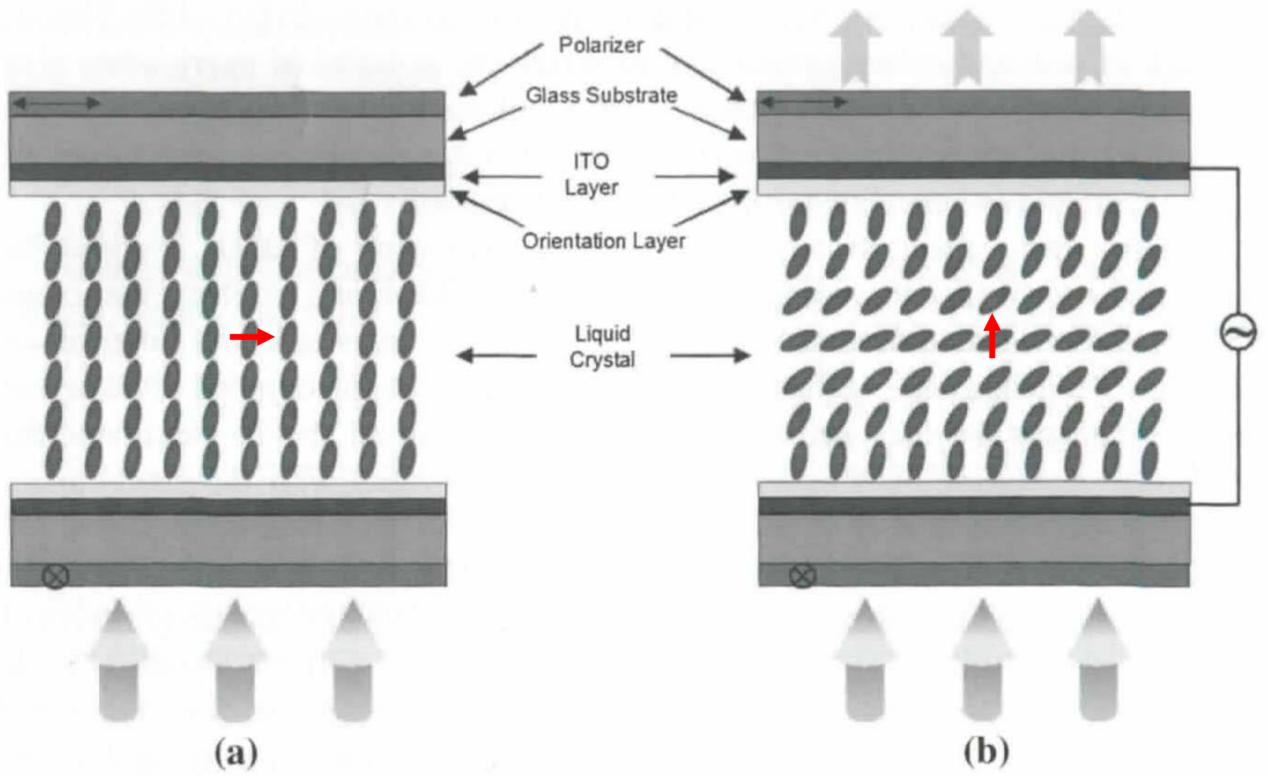
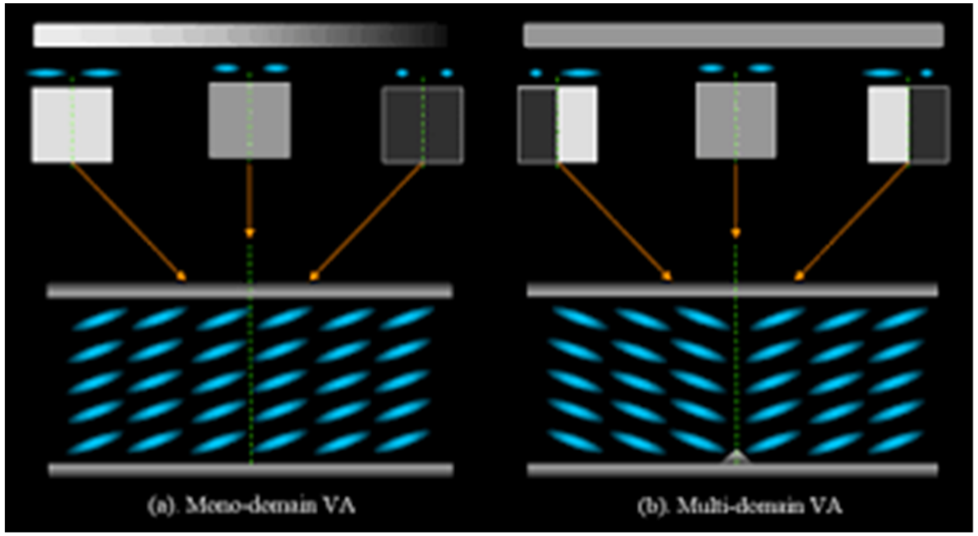


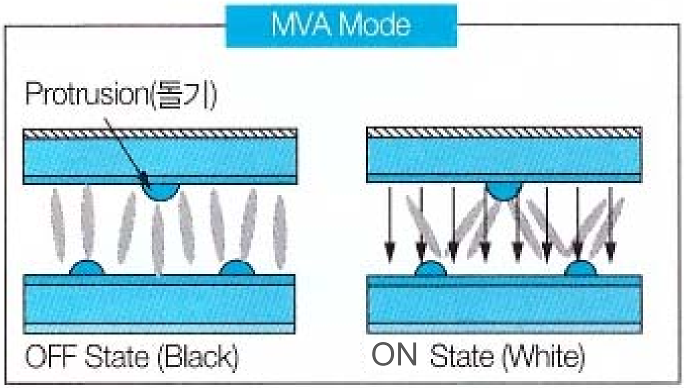
Fig. 4.10 Illustration of the normally black, VA mode of LC cell switching. **a** Zero bias dark-state. **b** Biased bright-state (Reprinted from [10] with permission of SID)

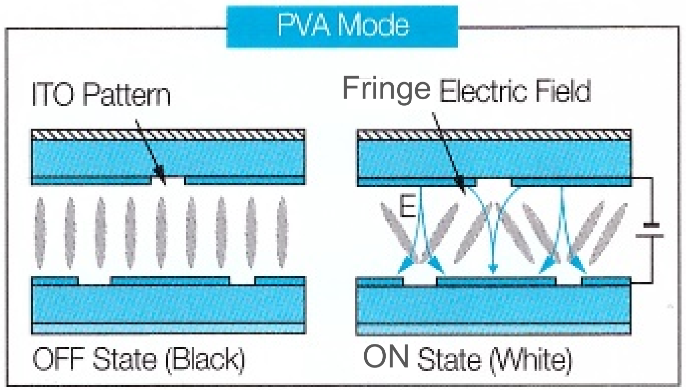
With the short axis vertically aligned, the long axis of the molecule is free to rotate within the horizontal plane, and, by sub-dividing and texturing the pixel surface, the long axis is constrained to lie in different directions within the sub-divided pixel.

Hence, in a pixel containing four sub-pixel domains, the same molecule orientation is seen from different angles, which greatly improves the viewing angle performance of the VA cell compared with conventional TN cell.



The average of the two is the same.





MVA: Multiple-Domain VA

PVA: Patterned VA (Samsung)