Chapter 2

Principle

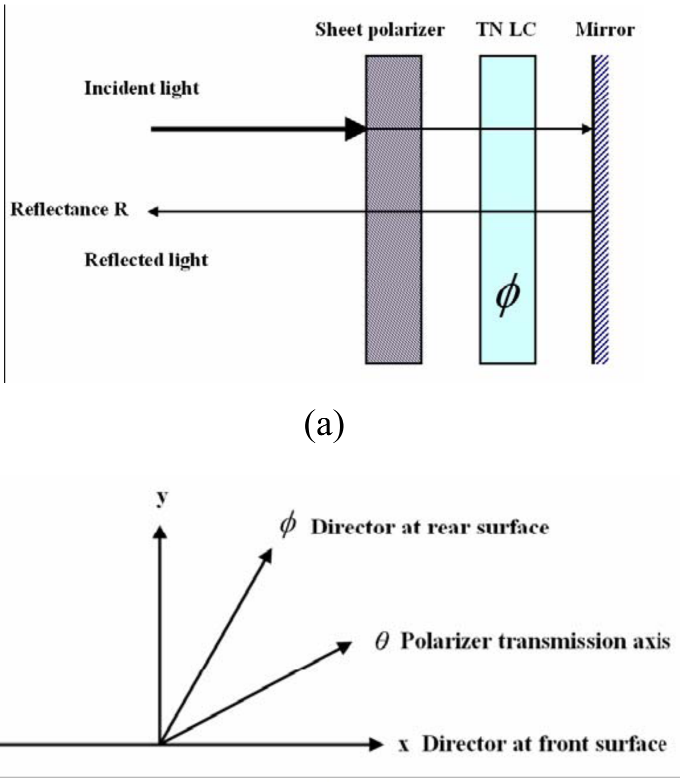
2.1 Overview

An overview of the basic principle of reflective LCD and EL display will be given in this chapter respectively. Then, the principle of the operation of the pixel circuit will be introduced. In addition, the proposed pixel circuit design will be shown.

2.2 Principle of Liquid Crystal Display

2.2.1 Reflective LCDs

Liquid crystals can be employed for display applications after by combining with the backlight. Transmissive LCDs require two polarizers to control the intensity modulation at each pixel. The input polarizer prepares a linear polarization state before entering the LC layer. The analyzer is employed to produce the black or the dark state. If the backlight is replaced with a mirror and the light is illuminated from the front, only one polarizer is needed since the light passes through the LC layer twice. For direct-view applications, the backlight is provided by the ambient light. Reflective LCDs can also be employed for projection displays. Next, the property of general twist nematic (TN) LCD with a back mirror which is employed in our design will be introduced. Referring to Fig. 2.1a, a reflective display that employs a TN-LC of STN-LC sandwiched between a sheet polarizer and a mirror is set up. This configuration is used for direct view reflective displays[11,12,13].



(a)

(b)

Fig. 2.1 (a) Schematic drawing of a direct view reflective LCD

(b) The azimuth angle of components in the reflective LCD

The x axis is chosen to be parallel to the director at the input surface. ϕ is the total twist angle of the LC layer, θ is the angle of the transmission axis of the polarizer. First, the reflection and transmission properties of the reflective LCD in the off state at normal incidence are considered. According to Fig. 2.1b, the incident and reflected polarization states, as determined by the orientation angles of the polarizer reflection axis, are given by

$$\begin{pmatrix} V_x \\ V_y \end{pmatrix} = \begin{pmatrix} \cos\theta \\ \sin\theta \end{pmatrix} \quad , \quad \begin{pmatrix} V_x' \\ V_y' \end{pmatrix} = \begin{pmatrix} \cos\theta \\ \sin\theta \end{pmatrix} \qquad (2\text{-}1)$$

where θ is the angle of the plane of polarization of the incident and reflected beam. Assuming an incident beam of polarized light, the intensity of reflectivity of the LCD shown in Fig. 2.1 is given by, according to the Jones matrix method

$$R=\frac{1}{2}\left|V'M^{T}MV\right|^{2} \tag{2-2}$$

$$M=\begin{pmatrix} \cos X-i\frac{\Gamma\sin X}{2X} & \phi\frac{\sin X}{X} \\ -\phi\frac{\sin X}{X} & \cos X+i\frac{\Gamma\sin X}{2X} \end{pmatrix} \tag{2-3}$$

where M is the Jones matrix of the LC cell, the M^T indicates a transpose operation of the matrix M, and V and V’ are the incident and reflected Jones vectors, respectively. Using Eq. (2- 1) for M, and Eq. (2- 3), after a few steps of matrix multiplication, the reflectivity is obtained that

$$\begin{gathered} R=\frac{1}{2}\left|A+iB\right|^{2} \\ A=\cos^{2}X+\phi^{2}\frac{\sin^{2}X}{X}-\frac{\Gamma^{2}}{4}\frac{\sin^{2}X}{X} \\ B=\frac{\Gamma\sin X}{X}\left[\cos 2\theta\cos X+\sin 2\theta\frac{\phi\sin X}{X}\right] \end{gathered} \tag{2-4}$$

where θ is the angle between the angle of the reflection axis of the PBS measured from the local director at the input surface, φ is the total twist angle of the LC cell, and X is given by

$$X=\sqrt{\phi^{2}+\left(\frac{\Gamma}{2}\right)^{2}} \tag{2-5}$$

The reflectivity can be written as

$$\begin{aligned} R=&\frac{1}{2}\left[\cos^{2}X+\phi^{2}\frac{\sin^{2}X}{X^{2}}-\frac{\Gamma^{2}}{4}\frac{\sin^{2}X}{X_{2}}\right]^{2} \\ &+\frac{1}{2}\left\{\frac{\Gamma\sin X}{X}\left[\cos 2\theta\cos X+\sin 2\theta\frac{\phi\sin X}{X}\right]\right\}^{2} \end{aligned} \tag{2-6}$$

By using the Mauguin parameter u such that

$$u=\frac{\Gamma}{2\phi}=\frac{\pi\Delta nd}{\phi\lambda}\text{，}\quad X=\phi\sqrt{1+u^{2}} \tag{2-7}$$

Eq. (2-6) can be rewritten as the following

$$R = \frac{1}{2}\left\{\cos^2 X + \frac{1-u^2}{1+u^2}\sin^2 X\right\}^2 + 2u^2\left\{\frac{\cos 2\theta \sin X \cos X}{\sqrt{1+u^2}} + \frac{\sin 2\theta \sin^2 X}{1+u^2}\right\}^2 \quad (2\text{-}8)$$

The transmission is given by

$$T=1-R \qquad (2\text{-}9)$$

In the case when a sheet polarizer is used, as shown in Fig. 2.1a, Eq. (2- 8) is the reflectivity of the reflective display system, where θ is the angle of the transmission axis of the polarizer measured from the local director at the input surface.

By examining Eq. (2- 8) for the reflectivity, it is found that for a given TN-LC or STN-LC cell with a twist angle φ and a Mauguin parameter *u*, the reflectivity R is a periodic function of the angle θ. By differentiating Eq.(2- 8) with respect to the angle θ, the following maximum and minimum reflectivity is obtained:

$$R_{\min} = \frac{1}{2}\left\{\cos^2 X + \frac{1-u^2}{1+u^2}\sin^2 X\right\}^2, \text{ when } \tan 2\theta_{\min} = -\frac{\sqrt{1+u^2}}{\tan X} \qquad (2\text{-}10)$$

And

$$R_{\max} = \frac{1}{2} \quad \text{when} \quad \tan 2\theta_{\max} = \frac{\tan X}{\sqrt{1+u^2}} \qquad (2\text{-}11)$$

According to Eq. (2-10)

$$R_{\min} = 0 \quad \text{when} \quad \tan X = \pm\sqrt{\frac{u^2+1}{u_2-1}} \qquad (2\text{-}12)$$

In summary, $R_{\min}$ is always possible provided the polarizer orientation angle θ satisfies the condition Eq.(2- 11). On the other hand, full reflection ($R_{\max}$=0.5) is possible provided that the Mauguin parameter satisfies the condition (2- 12).In other words, a normally black TN-RLCD which can switch reflectivity from 0 to 0.5 is possible through the designed setup.

2.3 Principle of EL devices

2.3.1 Electroluminescence

The electroluminescence devices are often modeled as diodes, which employ concepts of energy band theory and carriers transportation to explain electrical characteristics. The emitting principle of EL devices can also be explained in similar ways. The principles are illustrated in three stages, as shown in Fig. 2.2. When positive voltage is applied, the holes and electrons will be injected into the highest occupied molecular orbital (HOMO) of the hole transporting layer (HTL) and the lowest unoccupied molecular orbital (LUMO) of the electron transporting layer (ETL) respectively. In the second stage, the tilt energy band corresponds to electric field, and holes and electrons are transported to the junction of the HTL and the ETL. In third stage, the accumulated carriers on the junction recombine in the emissive layer to be excition. The exciton is either in singlet or in triplet-state according to the Pauli's principle. The exciton will form two new energy bands inside the band gap. As the excited state of the excition transits to the ground state, heat and photons accompany with the transition with an energy set according to the gap between the energy bands. The states of the excition have certain influence of the emission of light and quantum efficiency since the singlet states release its energy as an emission of photons. However the triplet-state is regarded as the heat forming state and can not transfer to light. In some special cases, the triplet-state generates light as well.

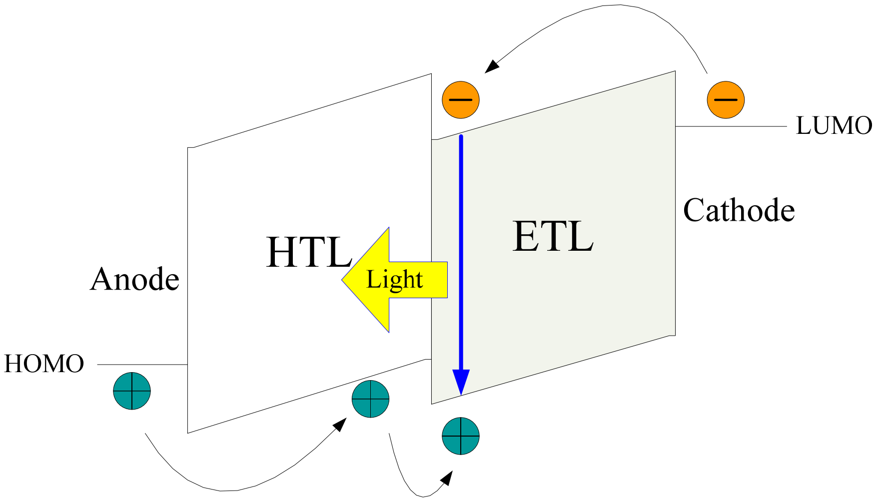


Fig. 2.2 Energy band diagram of OLED and electron-hole recombination in the forward bias condition

2.3.2 The Electroluminescence Structures

The EL structures can be divided into three types：Bottom Emission, Top Emission, and Transparent Emission. Conventional EL devices have thick metal cathode such as Al and Ag, and the metal cathode reflecting luminescence let devices emit light from bottom substrate. This is so called the bottom emission. If the metal cathode is transparent and the anode on the substrate has high reflectance, the emitting light will pass through the cathode. The device structure is named as the top emission. While the anode and the cathode are both transparent, the device emits light from double sides, so called transparent device [14]. As it was mentioned in Chapter 1, the total light efficiency of the device has many factors including the aperture ratio of the circuitry plane. As shown in Fig. 2.3, Aperture ratio defines the ratio of the amount of the transmitted light to one of the incident light. As shown in Fig. 2.4, the device severely sacrifices the aperture ratio for the bottom emission structure since the emitting light is blocked by the pixel circuitry. On the other hand, the top emission structure saves aperture ratio with transparent cathode, and it is beneficial to pixel circuit design.

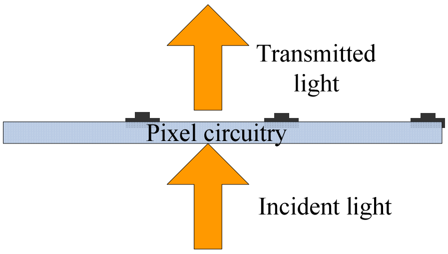
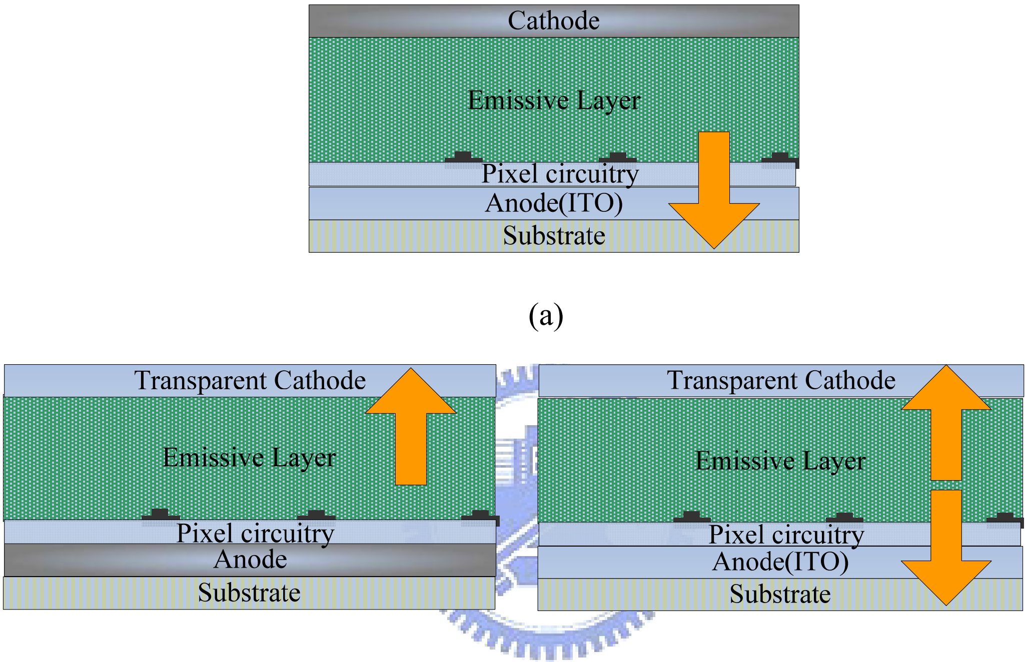


Fig. 2.3 Definition of aperture ratio



(a)

(b) (c)

Fig. 2.4 Structure of (a) bottom emission (b) top emission, and (c) transparent device

2.3.3 Passivation of EL Devices

The energy bandgaps between anode and HTL, or cathode and ETL play as important roles in the injection of the carriers, as shown in Fig. 2.2. In order to enhance the injection, it is often adopted to lower the injection energy barrier. The energy levels of the emission materials' LUMO are about 2.5~3.5 eV, and the energy levels of HOMO are 5~6 eV. The material of cathode must be metal with low work function to inject electrons into ETL, and the anode is the material with high work function. However, metal cathodes with low work function mean that the cathodes are easily oxidized. The oxidization of the cathode leads to the failure of the EL device. Thus, the encapsulation of the EL device isolates the water vapor and oxygen which cause damage to the EL device.

Conventional EL device is encapsulated with a glass lid by sealing glass lid on the device with glue in an inert atmosphere. This method increases the thickness of EL device and sacrifices display size for the gluing area. Moreover, the possibility of being flexible displays is obliterated.

By replacing these coverings with a thin film encapsulation (TFE) layer, the advantage of EL device in thickness is retained. It is unnecessary to waste display area for the sealing. Besides, the EL device is feasible to become flexible display. On the other hand, thin film encapsulation has to fulfill some requirement. First, the film serves as a good diffusion barrier to water and oxygen. Second, there is no pinhole on the films since no absorbent exists upon the EL device.

The thin film encapsulation is essential to our emi-flective display because the spacing between the EL device and the LCD must be small to eliminate the parallax effect. Moreover, the emi-flective display is possible for flexible display and active matrix device. As a glass lid is non-flexible and too thick to be etched to form the connection of the via, TFE provides emi-flective display an access to being flexible and active matrix device.

2.4 Addressing Schemes for LCDs and OLED Displays

2.4.1 Passive-Matrix Addressing

Passive-matrix (PM) addressing is used in earlier displays. Matrix addressing scheme means that only n+m control signal are required to address n * m pixels. The display is scanned row by row from the top to the bottom at a rate which flicker is hardly perceived. The necessary voltages provided by external drivers sequentially are determined by the voltage between the voltages of the column and row electrodes.

2.4.1.1 Passive-Matrix LCDs

The liquid crystal molecules are aligned to the electrical field to form gray level during the addressing time. After the addressing period, the liquid crystal molecules recover to the unbiased state. PM addressing has the advantages of low cost, matured fabrication process as the PM displays only require row and column electrodes. However, the insufficient addressing time, compared to response time of liquid crystal, results in blur images and low contrast ratio as the resolution of the panel increases. Nowadays, the PM addressing is replaced by active-matrix (AM) addressing for high-resolution displays.

2.4.1.2 Passive-Matrix OLED Displays

A passive-matrix array consists of two sets of electrically isolated conducting electrodes arranged orthogonally with an OLED to form the pixel at each intersection, and connected to the external drivers that supply the necessary voltage and timing sequence.The main issues of PM-OLED are full-color and resolution. In order to achieve the gray level, the time multiplexer is often employed. Dividing the current pulse into N sections as N bits will result in the problem of RC charging on each pixel. Moreover, the pixel duty factor of such a row-scanned array is 1/*Ns*, where *Ns* is the number of scan electrodes. Since the selected pixel must be driven with a pulsed voltage signal at a duty cycle, instantaneous luminance *L0* should be high enough to achieve an average display luminance *Ld*:

$$L_0 = N_s \cdot L_d \tag{2-13}$$

Even the EL response time is sufficient for pulse-driven passive matrix, the number of rows in an array limits the average display luminance. For example, an instantaneous luminance should be about 10000 cd/cm^2 to achieve an average luminance of 100 cd/cm^2 for a passive matrix with 100 rows. The high driving voltage and instantaneous current lower the OLED power conversion efficiency and lifetime.

2.4.2 Active-Matrix Addressing

Each pixel is attached to a switch-device, which actively maintains the pixel state while other pixels are being addressed, which also prevents crosstalk from inadvertently changing the state of an unaddressed pixel. The most common switching devices are Thin Film Transistors (TFT), i.e. a FET based on either the economical non-crystalline thin film silicon (a-Si), polycrystalline silicon (poly-Si), or CdSe semiconductor material.

2.4.2.1 Active-Matrix LCDs

Active-matrix (AM) LCD employs TFTs on the circuitry backplane as switches of pixels, and overcomes the issues of low response time, low contrast ratio. As shown in Fig. 2.5, each pixel consists of one TFT, one storage capacitor. The data voltage is written into the pixel during the addressing period, and storage capacitor maintains the voltage after addressing. AMLCD is only driven by voltage.

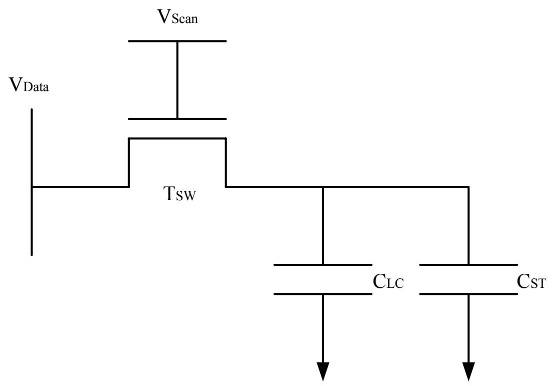


Fig. 2.5 Pixel configuration of active-matrix LCD

2.4.2.2 Active-Matrix OLED Displays

Using an active-matrix addressing can solve the image contrast and column electrode pattering concern of passive-matrix addressing. In the AM addressing, a transistor is placed at each pixel to separate the effect of the data line (column electrode) voltage and the scan line (row electrode) voltage on the voltage across the OLED material. A common cathode material (MgAg, Al-Li) is used to eliminate the need of patterning the electron injecting electrode. Within AM-OLED designs, a variety of pixel architectures have been proposed, such as voltage programming [15,16,17] and current programming circuits [18,19,20]. Different pixel architectures may contain different numbers of transistors per pixel. The simplest design uses one transistor per pixel which is similar to the pixel circuit for AM-LCD, as shown in Fig. 2.6. However, the voltage signal in storage capacitor C_{ST} is leaking out through OLED even switch transistor T_{SW} is closed. Therefore, each pixel is needed to pulse ON for a duty factor $1/Ns$ of the frame time. The high instantaneous OLED current much more than the average current still encounters the same issue of PM-OLED. In order to maintain stable current during the frame time, one n-channel TFT is employed to generate the current.

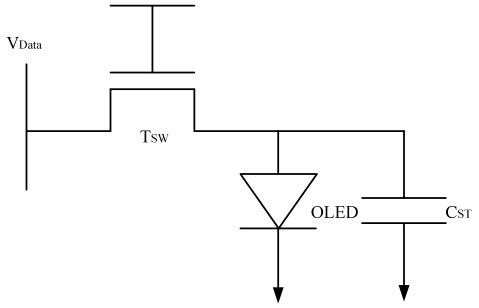


Fig. 2.6 1T1C pixel circuit for AM-OLED

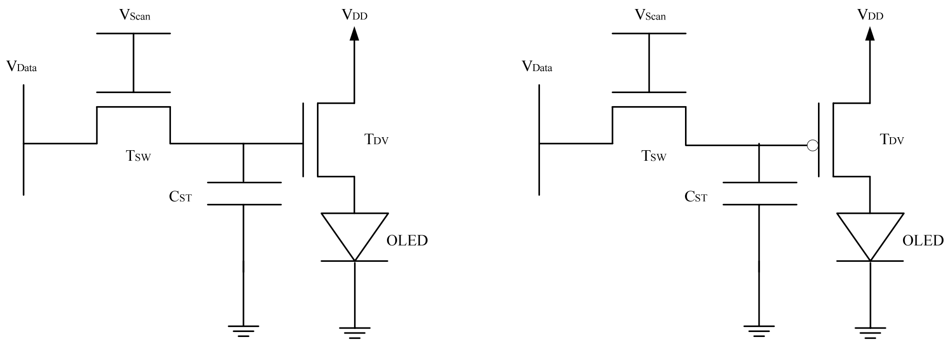
As shown in Fig. 2.7(a), the voltage data Vdata which is written into the pixel is not leaking out through OLED and maintained by storage capacitor C_{ST}. The OLED driving current I_{OLED} generated by n-channel T_{DV} is：

$$I_{OLED} = \frac{1}{2}\mu_{FE} \cdot C_{OX} \cdot \frac{W_{DV}}{L_{DV}} \cdot \left(V_{data} - V_{OLED} - |V_{TH}|\right)^2 \qquad (2\text{-}14)$$

where μ_{FE}, C_{OX}, W_{DV}, L_{DV}, V_{OLED} and V_{th} are the field-effect mobility, gate oxide capacitance per unit area, channel width, channel length, OLED cross voltage and TFT threshold voltage, respectively. With n-channel T_{DV} configuration, the data voltage should consider the OLED voltage V_{OLED}. On the other hand, p-channel T_{DV} is practical for this pixel circuit design, shown in Fig. 2.7(b), the OLED current is determined by the gate-to-source voltage：

$$I_{OLED} = \frac{1}{2}\mu_{FE} \cdot C_{OX} \cdot \frac{W_{DV}}{L_{DV}} \cdot \left(V_{DD} - V_{data} - |V_{TH}|\right)^2 \qquad (2\text{-}15)$$

Since the most commonly used technologies for conventional AM-LCD are a-Si and poly-Si TFTs, both of them are compatible with large area glass substrate processes, which is necessary to fabricate displays at reasonable cost. Poly-Si TFT technology was chosen for AM-OLED display because of its higher mobility and greater stability compared with a-Si TFT. In addition, poly-Si TFT technology has ability to provide p-channel devices for not only pixel circuits but also integrated drivers.



(a) (b)

Fig. 2.7 2T1C pixel circuit for AM-OLED with

(a) n-channel T_{DV} and (b) p-channel T_{DV}

2.5 Non-Uniformity of the OLED Panel

2.5.1 The Variation of Threshold Voltage

Threshold voltage (V_{th}) is the value of gate-to-source voltage (V_{GS}) at which a sufficient number of mobile electrons accumulate in the channel region to form a conduction region. V_{th} is of positive value for an n-channel device and negative for a p-channel device. The value of V_{th} is determined by the fabrication process. Not only poly-Si TFTs but also a-Si TFTs suffer from the variation of V_{th}. The V_{th} of a-Si TFTs increases due to the stress of long-lasting operation [21]. Poly-Si TFTs suffered from the threshold voltage shift caused by the eximer laser annealing (ELA) [22]. ELA was widely used in the process of poly-Si TFTs for the high processing throughput, however, the grain size of poly-silicon after annealing process was not uniform. Therefore, the threshold voltage shift severely influenced the image quality. From Eqs. (2-14) and (2-15), the variation of V_{th} varies the OLED current from pixel to pixel and lower the uniformity of the OLED panel.

2.5.2 IR-Drop

As the resolution of the panel increases, the resistance of the panel increases with the numbers of row and column electrodes. The V_{DD} line provides distinct voltages to the different pixels. As depicted in the varied voltage V_{DD} on each pixel leads to the non-uniformity of the panel.

2.6 Emi-flective Display of R-LCD and Electroluminescence Device

2.6.1 The Structure of the Emi-flective Display

The emi-flective display stacks R-LCD on the EL device. The structure, shown in Fig. 2.8, comprises the reflector, the ITO anode of the EL device, the transparent cathode of the EL device, the passivation layer, the bottom eletrode, the LC layer, the top electrode, and the polarizer sequentially from the bottom to top. The R-LCD in the hybrid display can be any mode of nematic liquid crystal displays, such as TN, STN, VA mode LCD or cholesteric liquid crystal display. It should be noted that there is no intermediate glass between R-LCD and the EL device.

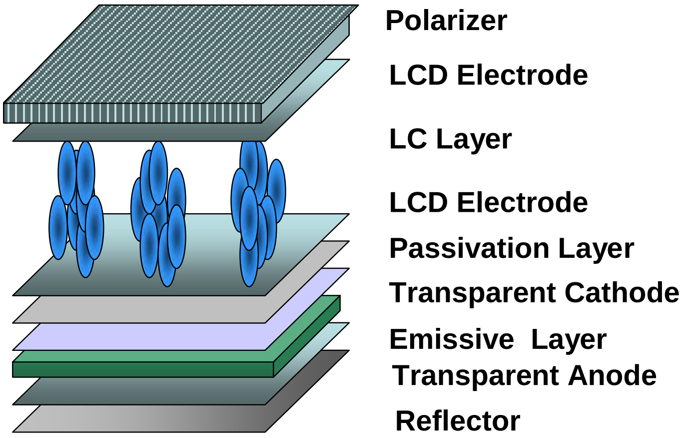
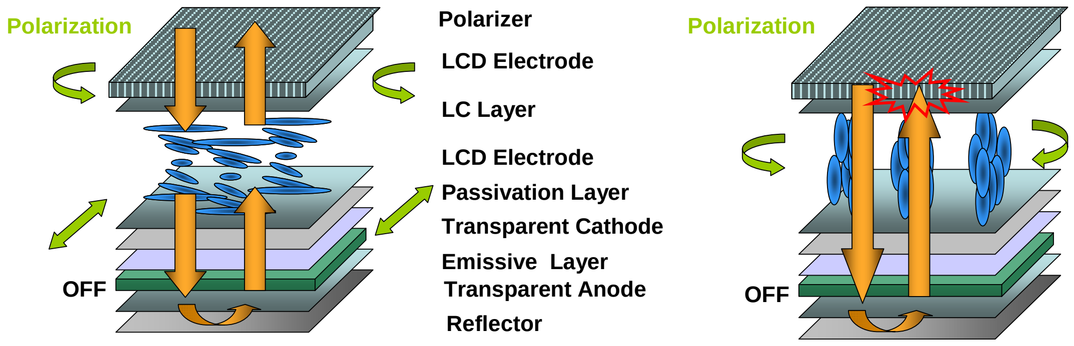


Fig. 2.8 The structure of the emi-flective display

2.6.2 The Operation of the Emi-flective Display

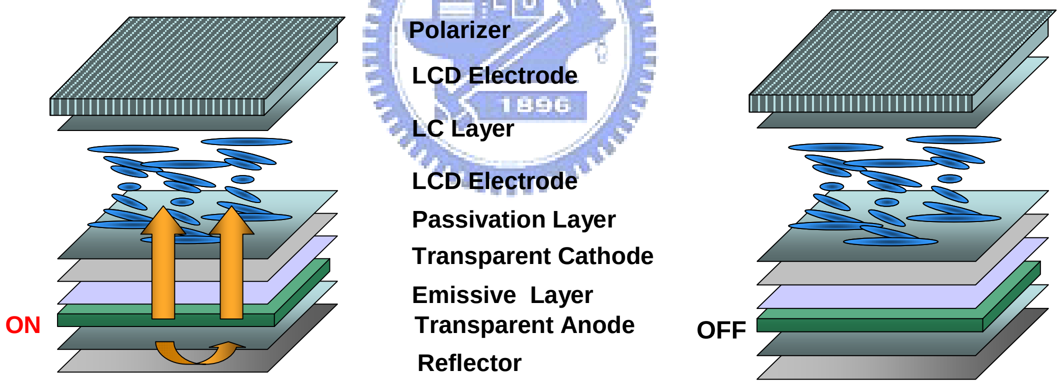
For the operation of the emi-flective display, it can be divided into the reflective mode and the emissive mode. For the explanation, a normally white TN LCD will be applied as the R-LCD part. For the reflective mode, EL device is turned off. The whole device works as R-LCD. The ambient light at normal incidence will pass through the circular polarizer and be circularly polarized. The polarized light passes through the LC layer and reached the reflector. Since the TN-LC can be taken as $\lambda/4$ plate, the polarization of light passing through the LC layer becomes linear polarization. After being reflected by the bottom reflector, the polarization of light will still be linear polarization, but 90°different from the original incident light. When linear polarized light experiences the LC layer at the second time, the LC layer will transfer linear polarization into circular polarization the same as the polarization of the original circular light. Thus, the bright state is obtained. When a voltage is applied to a R-LCD and the LC molecules are aligned to the electrical field perpendicular to the substrate. The incident ambient light passes through circular polarizer and experiences the LC layer. Since the LC molecules are aligned perpendicular to the substrate, the incident light undergoes no phase retardation. After being reflected by the bottom reflector, the polarization of the incident light transfers circular polarization into the other type of circular polarization. The circular polarizer blocks the returned polarized light with the other type of circular polarization, and the dark state is formed. The schematic operation is shown in Fig. 2.9

When the ambient light is not enough, the emi-flective display is operated in the emissive mode. For the emissive mode, R-LCD is unbiased. Generally, the light emitted from the EL device is isotropic. Thus, the upper half of the light will directly go up and pass through the LC layer and the polarizer. The lower half of the light will go down to the reflector, and go up after the reflection. Thus, the bright state is obtained. In the dark state, both EL device and R-LCD are switched off. There is neither emissive light from EL device nor the reflected ambient light. The schematic operation is shown in Fig. 2.10



(a) (b)

Fig. 2.9 (a) bright state and (b) dark state in the reflective mode



(a) (b)

Fig. 2.10 (a) bright state and (b) dark state in the emissive mode

2.6.3 The Pixel Circuit for Emi-flective Display

Because of no intermediate glass between R-LCD and EL device, the emi-flective display can be driven by one circuitry backplane. Here is the proposed pixel circuit for emi-flective display, shown in Fig. 2.11. This circuit comprises six p-channel TFTs, one capacitor. As shown in Fig. 2.12, four signal lines are employed in this circuit. As mentioned before, more TFTs and capacitors in each pixel will reduce the aperture ratio. However, the top emission EL device can compensate for the sacrificed aperture ratio. This circuit compensates threshold voltage variation of poly-Si TFTs and the deviated electrical characteristics of top emission OLED.

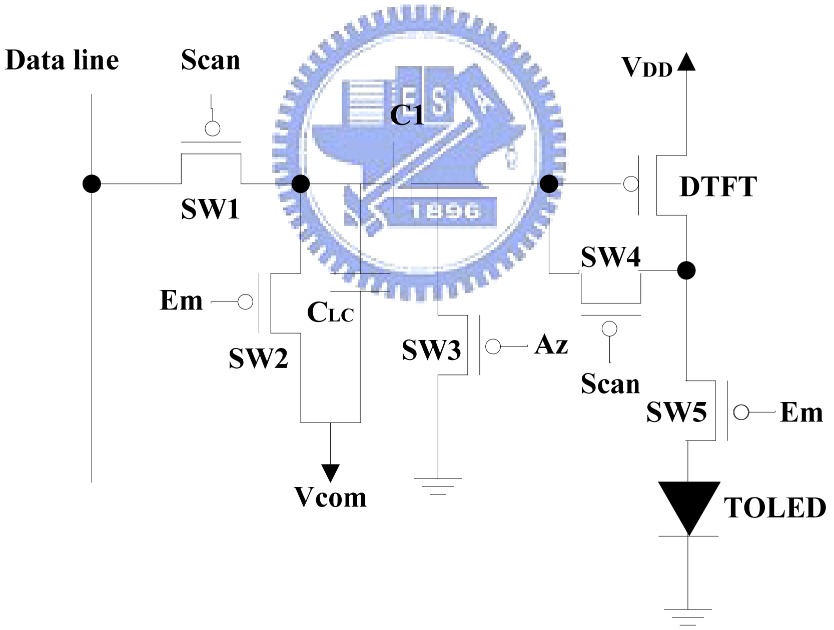


Fig. 2.11 The diagram of the proposed pixel circuit

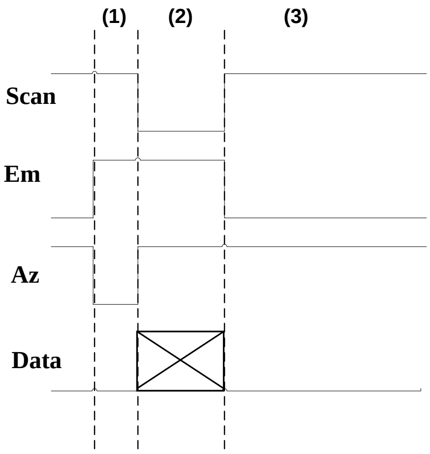


Fig. 2.12 Time diagram of the pixel circuit in the emissive mode

2.6.4 Operation of the Pixel Circuit

2.6.4.1 Operation in the Emissive Mode

When ambient light is dim, the emi-flective display is operated in the emissive mode. The addressing time is divided into three stages. In the initializing period, the gate voltage of DTFT (V_{G_DTFT}) was set to ground. In the addressing period, the SW5 was closed to prevent the current from flowing through the TOLED during addressing. The SW1 wrote the data voltage into the pixel. In the meantime, V_{G_DTFT} was charged to a potential owing to the diode connection of DTFT. As a result, V_{th} of DTFT was stored in the capacitor C1. V_{G_DTFT} could be described in Eq (2-16)

$$V_{G\_DTFT} = V_{DD} - \left|V_{th\_DTFT}\right| \tag{2-16}$$

In the illuminating period, the SW5 drove the TOLED current and TOLED illuminated. The SW2 held the R-LCD unbiased and solved the ion-charge effect of the issue which the previous work encountered [23] because the voltage of C1 was applied to Vcom by the SW2.Then there was no dc bias across R-LCD to induce image sticking. Moreover, V_{G_DTFT} was bootstrapped by C1 :

$$V_{G\_DTFT} = V_{DD} - \left|V_{TH\_DTFT}\right| - (V_{data} - V_{com}) \tag{2-17}$$

SW5 was turned on to allow current flowing through the TOLED and the current is determined by Eq (2-18):

$$
\begin{aligned}
I &= \frac{1}{2} k_p \frac{W}{L} (V_{DD} - V_{G\_DTFT} - \left|V_{TH\_DTFT}\right|)^2 \\
&= \frac{1}{2} k_p \frac{W}{L} \{V_{DD} - \left[V_{DD} - \left|V_{TH\_DTFT}\right| - (V_{data} - V_{com})\right] \\
&\quad - \left|V_{TH\_DTFT}\right|\}^2 \\
&= \frac{1}{2} k_p \frac{W}{L} \{V_{data} - V_{com}\}^2
\end{aligned}
\qquad (2\text{-}18)
$$

Thus, the TOLED current has immunity to ΔV_{TH} and turn–on voltage of TOLED.

2.6.4.2 Operation in the Reflective Mode

When ambient light is bright, the emi-flective display is operated in the reflective mode. The time diagram of signal lines is shown in Fig. 2.13. As the pixel circuit operated in the reflective mode, the signal voltages of Em and Az were set to high, and the signal voltage of scan line was set to low to write the data signal into the pixel The pixel circuit only varied the voltage across the RLCD and disenabled the luminescence of the TOLED because the SW5 blocks the TOLED current. Therefore, the operation in the LCD mode did not affect that in the TOLED mode. The simplified pixel circuit, shown in Fig. 2.14 is the same as conventional pixel circuit of AM-LCD.

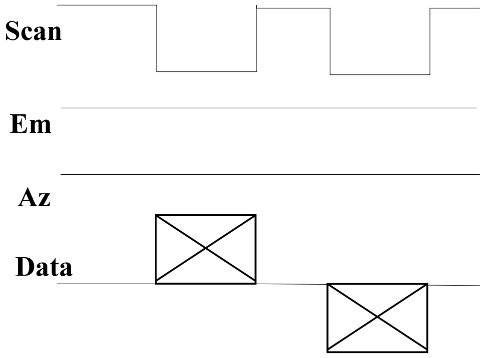


Fig. 2.13 Time diagram of the pixel circuit in the reflective mode

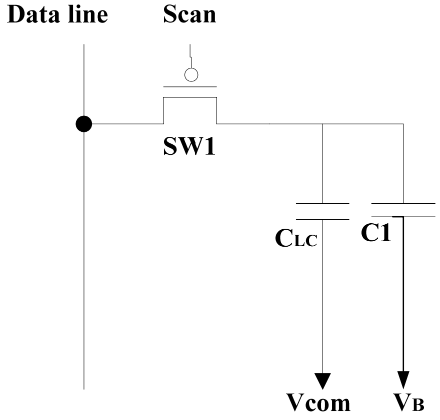


Fig. 2.14 The simplified pixel circuit in the reflective mode

2.7 Summary

The basic operation principles of R-LCD and EL device are introduced in this chapter. The addressing schemes for LCDs and EL devices including PM and AM are introduced and compared with each other. The emi-flective display without intermediate glass is proposed and feasible to become active-matrix or flexible display. In addition, the pixel circuit for the emi-flective display is also proposed to overcome threshold voltage variation of poly-Si TFTs and the deviated electrical characteristics of top emission OLED.