Jiun-Haw Lee | David N. Liu | Shin-Tson Wu



Introduction to

FLAT PANEL DISPLAYS

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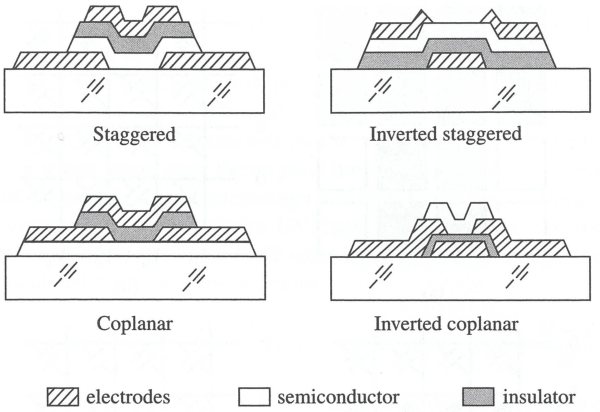


Figure 3.16 Different configurations of TFTs.[13] (Source: Powell, M.J. (1989) The physics of amorphous-silicon thin-film transistors. *IEEE Trans. Electron Dev.*, **36**, 2753. © 1989 IEEE.)

subthreshold swing from Figure 3.15(b). This is the inverse of the slope of $\log(I_D)$ versus V_G, in terms of V/decade. This parameter indicates how much voltage is needed to switch the TFT on and off. A smaller subthreshold swing is preferred since this results in higher speed and lower power consumption.

Typical TFTs can be categorized as normal or inverted structures, depending on whether their gate is on the top or bottom, respectively. Another classification depends on whether the drain/source and gate are on the same or opposite sides; these are called coplanar or staggered structures, respectively. Hence, there are basically four different kinds of TFT structures, which are shown in Figure 3.16. Different structures may be the result of different fabrication procedures and may result in different device performance. Typically, a-Si TFTs use the inverted staggered structure configuration because it makes them easy to fabricate and gives them better electrical characteristics. The a-Si channel is sensitive to photons of the external ambient that mainly illuminates from the bottom side in a display system: an inverted structure can shield the device from this light by virtue of the gate metal. Also, because of the laser irradiation recrystallization process to convert a-Si to poly-Si, a flat and continuous silicon thin film without other layers beneath is a better choice for low-temperature poly-Si (LTPS) TFTs. Hence, these devices typically make use of normal planar structures.

3.5 Passive matrix and active matrix driving schemes

To drive an LCD or OLED display, passive matrix (PM) and active matrix (AM) driving techniques are commonly used.[14, 15] For a PM LCD, due to the capacitor characteristics of the liquid crystal (LC) layer, a voltage applied to a selected pixel inevitably affects the neighboring pixels and degrades the contrast of the display, which is called crosstalk.[16] Each row of a PM LCD or OLED display is sequentially active with a high frequency, and the human eye regards it as a planar frame rather than line scanning due to the persistence of vision. Since only one row can be selected and displayed at a time, the display time for a single row decreases with increasing number of rows, which limits the display size and resolution. In contrast, by using TFTs in an LCD or OLED pixel, the turn-on/turn-off and different grayscales can be controlled independently: this is called AM driving.

Figure 3.17 shows the operation of a PM LCD. Electrodes in a stripe configuration are placed on two glass substrates. Stripes on the bottom and top glass substrates are aligned perpendicularly to work as column and row electrodes of the PM LCD, and each crossed section is a pixel region. LC material is filled between the two glass substrates, thus together they can be regarded as a capacitor. To display a

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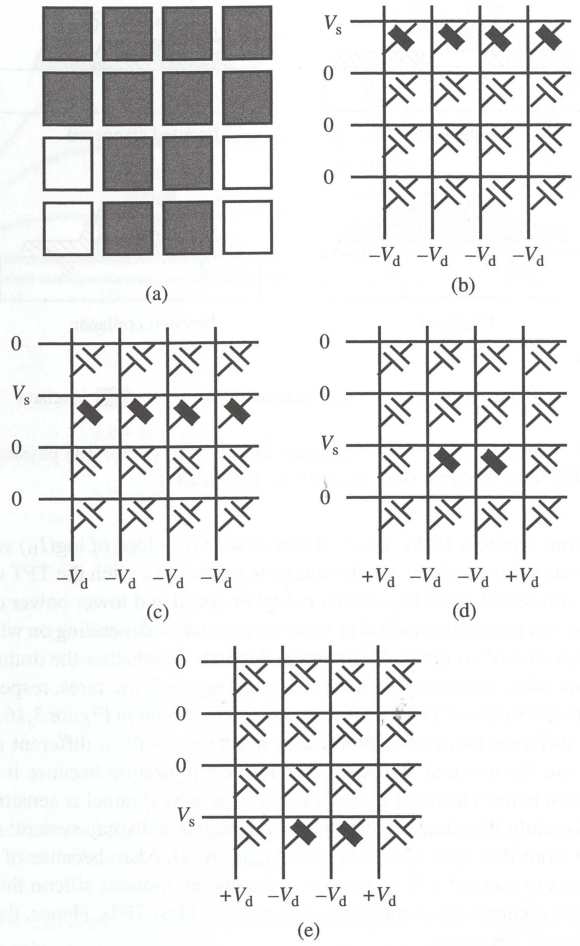


Figure 3.17 (a) Image displayed on a PM LCD, and the voltage at (b) first, (c) second, (d) third and (e) fourth time slots at each row and column.

'T' in a 4 × 4 LCD, the first row is first selected with a pulse voltage V_s for the first time slot, then the driving voltages from columns 1 to 4 are applied with $-V_d$, resulting in a voltage difference of $V_s + V_d$, and the left row lines 2 to 4 are applied with 0 V in root-mean-square (RMS) average (V_{rms}), so their voltage differences in the first time slot are V_d. Contrary to the V_D and V_S in Eq. 3.17 and 3.18, V_d and V_s here do not mean voltages at sources and drain, respectively, because it is PM driving without TFT. On the other hand, it represents voltages at data and scan lines. Then in the second time slot, the voltage on the row 1 electrode is reset to 0 V_{rms}, and the scanning voltage V_s is applied on row 2, and driving voltages for columns 1 to 4 are set at $-V_d$; hence only those pixels in row 2 have a voltage of $V_s + V_d$ and other pixels still experience a voltage difference of V_d. For the third time slot, scanning voltages for row 3 are V_s, but driving voltages for columns 2 and 3 are $-V_d$, and for columns 1 and 4 are $+V_d$; thus the voltage differences on pixels (3, 2) and (3, 3) are $V_s + V_d$, and voltages $V_s - V_d$ ($V_s + V_d$ for on, $V_s - V_d$ for off) are applied on pixels (3, 1) and (3, 4). In this slot, other pixels have voltages of either

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$-V_d$ or $+V_d$. A similar driving scheme is then applied for row 4 in the next time slot. Generally, the LCs will respond to the RMS value of the voltages they experience.

For a PM LCD with N row lines, if one row is selected, a voltage of V_s is applied on that row line to select all the pixels there, and V_d or $-V_d$ from the column line is then used to turn each pixel on or off. But neighboring pixels in the same column will also be affected by the voltage from the same column line. As a result, for a whole frame scan, the on pixel has a voltage of $V_s + V_d$ only for $1/N$ frame time, and has a voltage of V_d or $-V_d$ for the remaining $(N-1)/N$ frame time. Similarly, for a whole frame, the off pixel has a voltage of $V_s - V_d$ only for $1/N$ frame time, and V_d or $-V_d$ for the remaining $(N-1)/N$ frame time. Since LCs respond to the RMS value of the receiving voltage, the RMS value of on or off pixels can be calculated from the above schemes:

$$V_{on}^2 = \frac{1}{N}(V_s + V_d)^2 + \frac{N-1}{N}V_d^2 \text{ and } V_{off}^2 = \frac{1}{N}(V_s - V_d)^2 + \frac{N-1}{N}V_d^2.$$

So, on average, different pixels of a display can be made to achieve on or off states by setting appropriate V_s and V_d values. Also, the difference between V_{on} and V_{off} of this display is related to the number of rows N. For a practical LCD with a set voltage–transmittance curve, the difference between V_{on} and V_{off} cannot be zero; thus the maximum row number of the display is limited.

Figure 3.18 shows the operation of a PM OLED. Here, we take a diode to illustrate the OLED display. As in the LCD case, to display a 'T' in a 4 × 4 OLED display, the first row is selected with a low voltage. The four OLEDs in the first row are biased at high voltage when the column lines are turned on. Then, for the next time slot, the second row is biased with low voltage, and so forth. The advantages of the PM OLED include ease of fabrication and low cost. However, since each row is

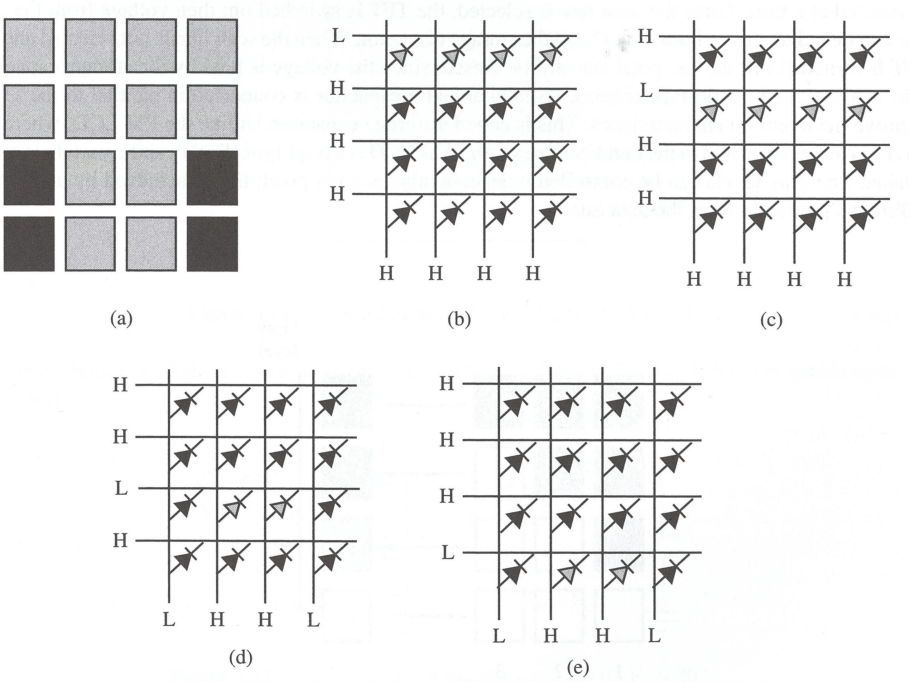


Figure 3.18 (a) Image displayed on a PM OLED, and the voltage at (b) first, (c) second, (d) third and (e) fourth time slots in each row and column.

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selected at a short time slot, the average luminance is the peak luminance over the number of rows. When the number of rows increases, the peak luminance needs to be very high, which shortens the device lifetime.[17]

There are some differences between OLEDs and LCDs as regards PM driving. For an OLED, each individual pixel has a fast turn-on time that is close to or faster than each slot time; thus the luminance for each pixel reaches a peak from this turn-on slot, and is then averaged over all the rows (or scanning time). In contrast, for an LCD, the LC response time is usually slower than the turn-on slot time; thus, for a single scanning slot with high voltage, there might not be enough time to respond to reach peak transmittance before the voltage is reset at the next time slot. But LCs will respond to the average RMS voltage value and output a transmittance according to this RMS value.

Each pixel in a single frame of a PM LCD and PM OLED has on and off states, which means it has two gray levels, 0 and 1. To realize more gray levels for PM displays, pulse width modulation (PWM) is usually applied as one of the common driving schemes. That is, the pulse width on a pixel is controlled to obtain more gray levels. Due to the persistence of vision, the human eye receives the time-average brightness. As shown in Figure 3.19, a frame with two gray levels is divided into three time intervals which are displayed sequentially to obtain four gray levels. When three time intervals are all dark, the resulting screen is also dark (gray level 0). However, if one of the three is bright, then the screen looks dark gray (gray level 1). On increasing the number of bright time intervals, one can perceive that the ultimate color becomes light gray (gray level 2) and then white (gray level 3). Hence, there are four gray levels now controlled by the pulse width. For PM LCDs, due to the slow response of LCs, blurring of the image may occur when displaying moving pictures.

For a display with a greater number of rows (higher resolution or larger size), the AM driving technique using TFTs is typically used. Figure 3.20 shows the equivalent circuit of an AM LCD. Only one scan line is selected at a time. Once the scan line is selected, the TFT is switched on; then voltage from the data line can be fed to charge both the LC and the storage capacitor. When the scan line is not selected and the TFT is switched off, the LC pixel can still be biased, since the voltage is held by the storage capacitor. This is also called a hold-type display. Usually an extra capacitor is connected in parallel to the LC to improve the retention characteristics. This is called a storage capacitor. Unlike the PM LCD, where the driving voltage is related to the number of rows, the AM LCD is a hold-type display and crosstalk is much weaker. The gray levels can be controlled independently for each pixel; this is achieved by applying a different V_D directly from the data line.

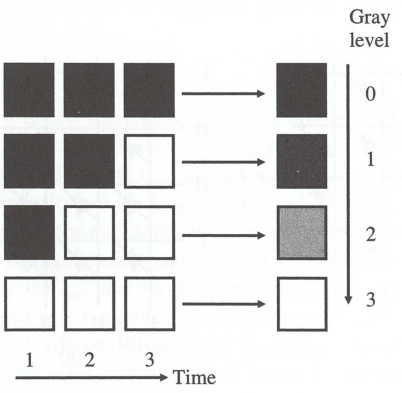


Figure 3.19 Four gray levels achieved by PWM.

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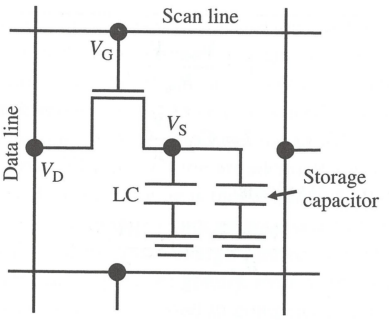


Figure 3.20 Equivalent circuit of an AM LCD.

Example 3.2

For the equivalent circuit shown in Figure 3.20, find the charging time of the LC, i.e. V_S, from 0 to 4.5 V_{rms} with $V_D = 5$ and 9 V_{rms}, respectively. V_D is always kept at 5 and 9 V_{rms}, while V_G is a step function which jumps from 0 to 20 V_{rms} at $t = 0$. There is no charge stored at LC ($V_S = 0$ V_{rms}) for $t < 0$. Timing diagrams of V_G and V_D are shown in Figure 3.21. When $V_G = 0$ V_{rms}, the leakage current can be neglected (open circuit, $R_{off} = \infty$). When $V_G = 20$ V_{rms}, the TFT can be replaced by a resistor with $R_{on} = 5$ MΩ The capacitance of the LC layer (including storage capacitor) is $C_{LC} = 3$ pF.

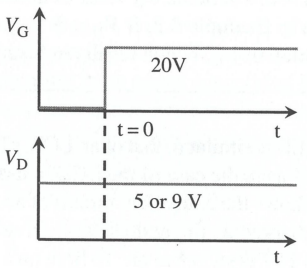


Figure 3.21 Timing diagram of V_G and V_D of Example 3.2.

Answer. Figure 3.22 shows the equivalent circuit when $V_G = 0$ and 20 V_{rms}. When the gate is open at $t = 0$:

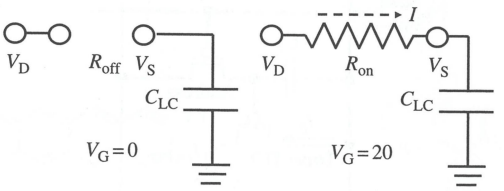


Figure 3.22 Equivalent circuit for (a) $V_G = 0$ and (b) $V_G = 20$ V.

(continued)

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$$I = \frac{V_D - V_S}{R_{on}}, \tag{3.20}$$

$$I = C_{LC}\frac{dV_S}{dt}. \tag{3.21}$$

Equating Equations (3.20) and (3.21) yields

$$\frac{V_D - V_S}{R_{on}} = C_{LC}\frac{dV_S}{dt} \tag{3.22}$$

or

$$R_{on}C_{LC}\frac{dV_S}{dt} + V_S = V_D. \tag{3.23}$$

Solving this differential equation, we obtain

$$V_S = V_D[1 - \exp(-t/\tau)], \tag{3.24}$$

where

$$\tau = R_{on} \times C_{LC}. \tag{3.25}$$

Hence, for V_S, from 0 to 4.5 V_{rms} with $V_D = 5$ and 9 V_{rms}, the charging times are 34.5 and 10.4 μs, respectively. In reality, the gate signal is only applied for a very short time in a TFT LCD. For example, for a panel with resolution of 1024 × 768 at a frame rate of 60 Hz, the V_G duration is only $1/(60 \times 768) = 21.7$ μs. Hence, a suitable V_D value is needed to achieving the desired V_S at such a short time slot. As shown in Example 3.2, if $V_D = 5$ V_{rms}, the charging time from 0 to 4.5 V_{rms} is even longer than the duration of V_G, which results in insufficient charging of the LC cell.

The AM driving method of an OLED is similar to that of an LCD. However, since an OLED is a current-driven device, rather than a capacitor as in the case of the LCD, a more complicated circuit is needed for an AM OLED display. Figure 3.23 shows the equivalent circuit of an AM OLED pixel. Typically, at least two TFTs are required, which are marked as the address and drive TFTs. When the electrical pulse is scanned to a certain row, the address TFT is switched on. To light on a particular pixel in this row, data line is selected, and the current provided by the power line passes through the drive TFT onto the OLED. Note that there is a capacitor, which can hold the voltage when the scan line is deselected, which means that the OLED keeps emitting light when the row is not selected. Hence, the peak luminance of AM OLEDs

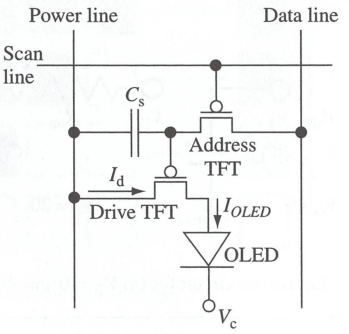


Figure 3.23 Equivalent circuit of an AM OLED with a two-transistor and one-capacitor configuration.[15]

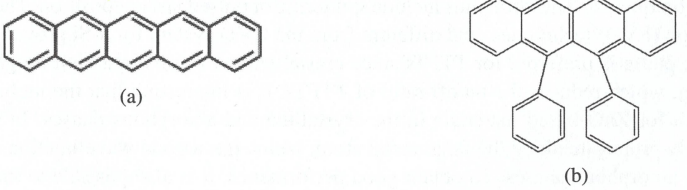
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does not need to be as high as that of PM OLEDs to achieve the same average brightness for each frame, which also extends the operation lifetime and makes a larger size display possible. This kind of pixel design is typically called a two-transistor and one-capacitor configuration. Here, the requirements for the address and drive TFT are quite different. The address TFT is used as a switch, and hence the on/off ratio is important. The drive TFT is used to provide current to the OLED, and hence a high current density capability is required. For the drive TFT to provide an adequate current, a high mobility is typically required. From this viewpoint, the LTPS technique is more suitable for driving the OLED. However, the uniformity achieved using the LTPS technique is not as good due to the laser annealing process. Since the J–V characteristics of OLEDs follow space charge limited current or trap charge limited current, described in Chapter 7, the current density varies greatly, even with a small driving voltage difference. Therefore, more than two TFTs are sometimes used to compensate for the nonuniformity of the LTPS TFTs and ensure a stable current density. To achieve different gray levels of the AM OLED, voltage modulation from the data line or PWM can be applied. The voltage modulation scheme in AM OLEDs is similar to that in AM LCDs. However, due to the steep luminance–voltage curve of OLEDs, it is not easy to control the gray levels precisely and uniformly. In the case of PWM driving, due to the higher frame rate, the power consumption is higher and the control system is more complicated.

3.6 Non-silicon-based thin-film transistors

In this section, we will introduce two kinds of TFTs where the active layer consists of organic molecules and ZnO-based materials. Organic TFT (OTFT) can be fabricated with a low temperature deposition and a solution process, which is less complex compared with conventional Si-based technologies. In addition, due to the mechanical flexibility of organic material, OTFT can be used as the backbone of the flexible display, and this has the benefit of being rugged, thin and lightweight.[18] Also, it is potentially of low cost due to the possibility of using the roll-to-roll process. When fabricating a flexible display on a plastic rather than a glass substrate, one important issue arises concerning the durability of the substrate.

Several methods can be used to form the organic thin film. For organic materials with lower molecular weight which can be evaporated or sublimated, one can heat up materials in a vacuum chamber to deposit the organic thin film on the substrate. Pentacene is one of the most common low molecular weight organic materials used for p-channel TFTs. The molecular structure of pentacene is shown in Figure 3.24(a). The mobility value of OTFTs is varied by varying many parameters, such as molecule stacking configuration, surface morphology and grain size. By controlling the fabrication parameters such as deposition rate and substrate temperature, one may obtain pentacene with a larger grain size. The mobility of pentacene-based TFTs can be as high as 0.7 $cm^2\ V^{-1}\ s^{-1}$, which is comparable to that of a-Si TFTs.[19] By growing a single-crystal organic thin film such as rubrene (the molecular structure of which is shown in Figure 3.24(b)), the mobility value of an OTFT can exceed 20 $cm^2\ V^{-1}\ s^{-1}$.[20] Also, one can dissolve the organic materials in certain solvents. This makes it possible to spin-coat, inkjet-print, stamp or imprint the solution on the



(a) (b)

Figure 3.24 Molecule structures of (a) pentacene and (b) rubrene.

Introduction to

FLAT PANEL DISPLAYS

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Flat Panel Displays (FPDs) are a frequent feature in our daily lives, used in mobile phones, laptop computers, desktop computer monitors and TVs. Several display technologies have been developed for FPDs, such as liquid crystal display (LCD), plasma display panel (PDP), light emitting diode (LED), organic light emitting device (OLED) and field emission display (FED).

Introduction to Flat Panel Displays describes the fundamental sciences behind each display technology: LCD, PDP, LED, OLED and FED including carbon nanotubes. It contains a comparative analysis of the different display technologies in which detailed overviews of each technology are linked together so as to provide a comprehensive reference for students and display engineers, alike. Solved problems as well as homework problems are provided in each chapter. Solutions are hosted on an accompanying website.

Senior undergraduate and graduate students taking courses in engineering, physics and chemistry will benefit from the systematic approach used throughout the book, which will help to prepare students for entry into a display profession. Display engineers, research scientists and technicians working on the development of flat panel display technology will also find this book an invaluable resource. Comparisons of the strengths and weaknesses of each of the display technologies will help professionals to decide which to use for their applications.

Features include:

- the classifications and specifications of display technologies as guidelines for developing a display and judging its performance;
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