

Chapter 2

Overview of All Pixel Circuits for Active Matrix Organic Light Emitting Diode (AMOLED)

2.1 Introduction

Organic light emitting diodes (OLED) displays are being actively developed recently accompanied by the rapid enhancement of OLED device performance such as luminous efficiency and long lifetime [2.1]-[2.2]. Because of various superior performance including self-emissive characteristic, simple structure, high contrast ratio, high brightness resulted from high emission efficiency, fast response time, wide viewing angle, and low cost [2.3]-[2.5], OLED displays show great potential to replace liquid crystal displays (LCDs) in several applications. OLED displays can be driven either by passive matrix (PMOLED) or active matrix (AMOLED) according to its driving method. Although most of the displays in commercial products are passively addressed with low fabrication cost and easy structure [2.6], they are biased during a short period, so higher current and higher voltage are necessary to achieve average brightness across the panel. This would dissipate more power and degrade OLED device rapidly. Therefore, active matrix driving method using low-temperature polycrystalline silicon thin film transistors (LTPS TFTs) is better for the high resolution displays in the future with the advantages of smaller number of

interconnections to peripheral electronics, low power consumption and, low fabrication cost. In the active matrix driving scheme, two transistors and one capacitor in each pixel are necessary for OLED to achieve the continuous illumination throughout the whole frame time [2.7] and the driving transistors are used to control different gray scales of the display brightness. Although the conventional pixel circuit with simple scheme has relative high aperture ratio, it encounters the problems of non-uniform brightness and poor gray scale accuracy in each pixel due to the electrical characteristic variation of the transistors and OLED. In attempts to achieve better image quality, many companies and academic circles increase the number of transistors in one pixel to compensate for the non-uniform problems in transistors.

Recently, several solutions for obtaining uniform brightness are proposed, such as digital driving method, voltage programming method, current programming method and novel driving method [2.8]-[2.16]. Digital driving method can provide excellent image uniformity because each OLED device is connected to a switch, but it is not suitable for the high-resolution displays. Voltage driving method operates by applying image signals to pixels as voltage data, which are converted to current data for OLED by pixel driving transistor and the current data have a nonlinear relationship to the voltage data. Although mobility variation still exists in the voltage programmed circuits, it is not as significant as threshold voltage variation when the driving transistor is operated in the saturation region [2.17]. Besides, a simple architecture of poly-Si data driver that is compatible with LCD drivers can be utilized and integrated on the display panel for realizing the objective of system on panel (SOP). As for current driving method, it works by applying image signals to pixels as current data, which then flows from driving transistor to the OLED device and the current data has a linear relationship with OLED luminance [2.18]. In the current programming pixel circuit, variation of the devices such as threshold voltage variation and mobility variation can be compensated effectively and the brightness can be controlled

directly by the applied data current. However, the long charging time of the data line capacitive load becomes a problem when the programming data current is low, especially in the high level displays. In addition, the data drivers are more complicated than those for voltage programmed circuits [2.19]. Unlike digital driving and analog driving, novel driving method involves the clamped inverter driving where OLED is only driven by either on state or off state of the driving amplifier which is applied by the varied analog signal.

In this chapter, all the pixel circuits for AMOLED are introduced and explained with their operation principles, advantages and disadvantages. They are classified into digital driving circuits, analog driving circuits and novel driving circuits from the view of operation mode of the driving transistor and the external applied signal source. Digital driving circuits employ area ratio gray scale (ARG) [2.20] method and time ratio gray scale (TRG) [2.9] method to obtain different gray scales while analog driving circuits are divided into voltage programmed circuits and current programmed circuits based on the applied input signals. Novel driving method, which differs from digital driving and analog driving methods, involves the clamped inverter driving method that each pixel circuit performs digital operation by varying the analog voltage signals.

2.2 Digital Driving Circuits

Digital driving method, as implied by the name, enables the driving transistor to operate in the digital mode, that is, either completely in the on state or completely in the off state, so each OLED element is just connected to an analog switch. This can be easily accomplished by applying either high voltage or low voltage to the pixel signal line. Because the image uniformity is almost not influenced by the TFT characteristics, a more uniform brightness image with the full digital operation can be achieved [2.21]. In the digital driving circuits, one important issue is how to maximize the number of gray scales

and the resolution. In this section, two gray scale control methods are introduced, which are area ratio gray scale (ARG) control [2.21] or time ratio gray scale (TRG) control [2.10]-[2.11].

2.2.1 Area Ratio Gray Scale Control (ARG)

For area ratio gray scale, each pixel is divided into some sub-pixels and the area of each sub-pixel can be equal [2.22] or weighted by a binary [2.20]. In the former method, each sub-pixel element yields the same brightness and the pixel brightness is proportional to the number of the sub-pixels in the on state. The number of gray scale is equal to the number of sub-pixels plus one (dark state; every sub-pixel is turned off). In the later method, the area ratio of the sub-pixels is $2^0 : 2^1 : 2^2 : \dots : 2^{n-1}$ and the brightness is proportional to the area of the sub-pixel when they are in the on state. Because the driving TFT utilized here is either completely on-state or completely off-state, 2^n gray scales can be obtained. For example, when $n=2$, the area ratio of sub-pixels is 1 : 2 as shown in Fig. 2.1. It can be observed that there are four different cases totally, namely four gray scales can be acquired finally. This type of gray scale is not expected to apply to the high resolution displays with large gray scale since the decrease of sub-pixel area and further increase of the number of sub-pixels may need high-end process.

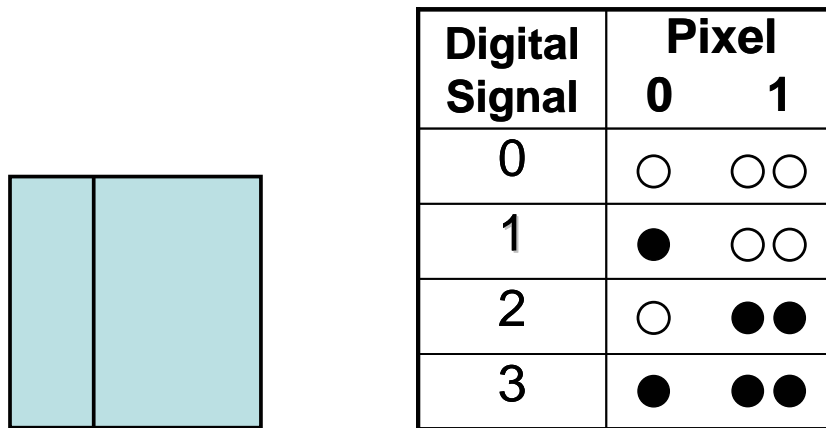


Fig. 2.1. Gray scale theory of area ratio gray (ARG).

2.2.2 Time Ratio Gray Scale Control (TRG)

In the time ratio gray scale (TRG) method, each frame is divided into several sub-frames and the brightness is controlled by adjusting the duration of light-on state. For example, one frame of the 5-bit gray scale is divided into five sub-frames as shown in Fig. 2.2. Each sub-frame consists of an addressing period and a lighting period. The conventional pixel circuit consists of two transistors and one capacitor is employed in this case. In the addressing period, a signal voltage is applied and stored in the gate voltage of the driving TFT. Every OLED pixel is not emitting because a high voltage is applied in the cathode. Shifting to the lighting period, the low voltage is applied to the cathode and every pixel with signal voltage which is held in the capacitor becomes bright [2.23]-[2.24]. After that, the next sub-frame period follows the previous sub-frame. The lighting period of each sub-frame is set up in a length proportional to the exponent of 2, that is, 1 : 2 : 4 : 8 : 16. Therefore, 5-bit gray scale which refers to 32 gray scales can be obtained. Besides this so-called display period separated (DPS) driving, another modified TRG was also developed which is called simultaneous erasing scan (SES) [2.25]. In SES, one additional transistor is

added for erasing switch, so the cathode voltage can be fixed. In addition, the length of a frame is cut down because some periods are not needed. Although time ratio gray scale (TRG) method appears to be suitable for small panel size displays, it requires fast addressing time, large power consumption and frame memories in the sub-frame data driver.

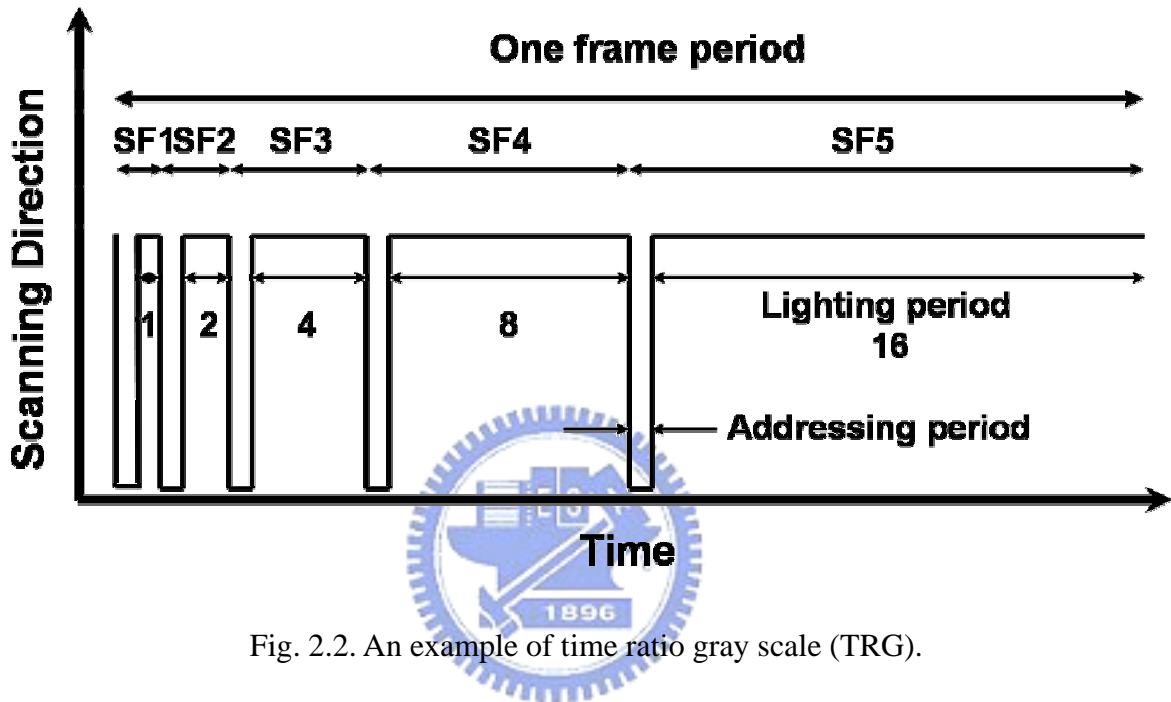


Fig. 2.2. An example of time ratio gray scale (TRG).

2.3 Analog Driving Circuits

For analog driving circuits, each OLED device is driven by a controlled current source and each pixel can be programmed either by a voltage source or a current source. The critical issue of the analog circuits is to select the right driving transistor and to construct the accompanying pixel design to ensure that the current source for OLED is insensitive to the spatial variations such as threshold voltage variation (ΔV_{th}) and mobility variation ($\Delta \mu$). In this section, a lot of analog circuits are classified into voltage programmed circuits and current programmed circuits according to the external applied signal source. In addition, the detail information of operation principle with their pixel circuit scheme and timing diagram

is also shown and discussed.

2.3.1 Voltage Programmed Circuits

2.3.1.1 Self-Compensation

It is well known that the variation can be introduced in the manufacturing process resulting in that the threshold voltage of one TFT would not be exactly the same as that of another one in the pixel. And the so-called self-compensation circuit is performed by compensation of own threshold voltage variation of the driving TFT. There are two main stages in the operation period. One is for calibrating out the variations in the transistor and OLED, and the other stage is for receiving the signal data voltage by the external applied data line [2.26]-[2.28]. Fig. 2.3 shows one of the pixel circuits with its timing diagram which was first proposed by Dawson in 1998. An auto-zero driving is first executed, which supposedly detects the threshold voltage of driving TFT MN2 and stores the necessary charge at the gate by storage capacitor C2. The gate terminal of MN2 is then floated when data signal is passed through C1 to the gate of MN2. As a consequence, the signal data voltage with the compensation of threshold voltage is applied onto the gate of the driving transistor. Therefore, the drain current for OLED will be insensitive to the variation of the driving transistor. However, two independent control signals (AZ and AZB) are used leading to the interconnection to each pixel and peripheral drivers rather complex. Moreover, the timing diagram is also very complicated and hard to comprehend.

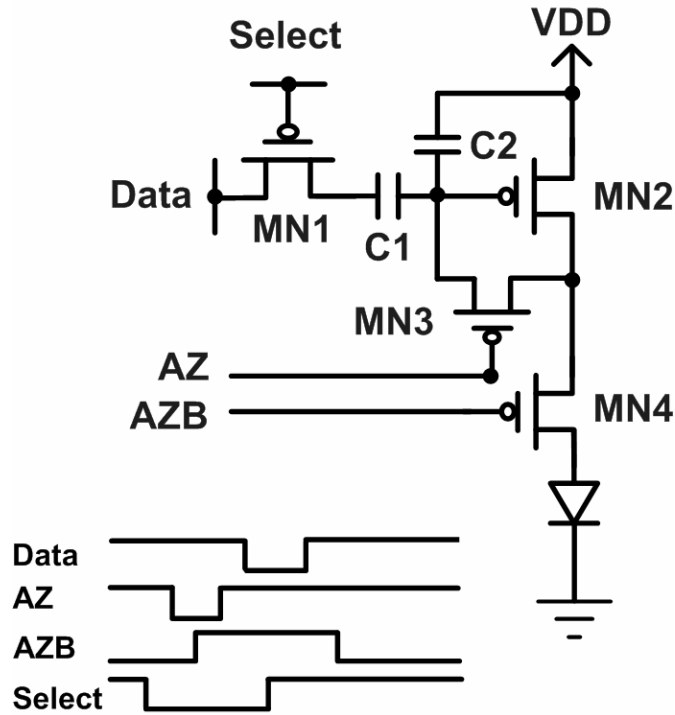


Fig. 2.3. Self-compensation pixel circuit with the timing diagram.

2.3.1.2 Diode Connection

For the diode connection method, the driving transistor is diode-connected during programming. In the n-type pixel circuit, the gate terminal of the driving TFT is in connection with its drain terminal [2.30]-[2.31], namely the anode of the resulting diode whereas in the p-type circuit, the gate terminal of the driving TFT is connected to the cathode of the resulting diode [2.32]. Unlike self-compensation method, the compensation stage is carried out along with the signal input stage. Fig. 2.4 shows this kind of diode connection pixel circuit [2.33]. During the programming period, gate to source voltage (V_{gs}) of the driving TFT T4 is V_{th} and the voltage stored in the storage capacitor equals to $V_{data} + V_{th} - V_{ss}$. When T4 is operated in the saturation mode, the drain current for OLED will be

$$I_{OLED} = \frac{1}{2} k_4 (V_{gs_T4} - V_{th_T4})^2 = \frac{1}{2} k_4 (V_{data} + V_{th_T4} - V_{ss} - V_{th_T4})^2 = \frac{1}{2} k_4 (V_{data} - V_{ss})^2, \text{ where}$$

$$k_4 = \mu C_{SiNx} \frac{W_4}{L_4}$$

Therefore, the drain current for OLED is independent of threshold voltage and is only affected by data voltage.

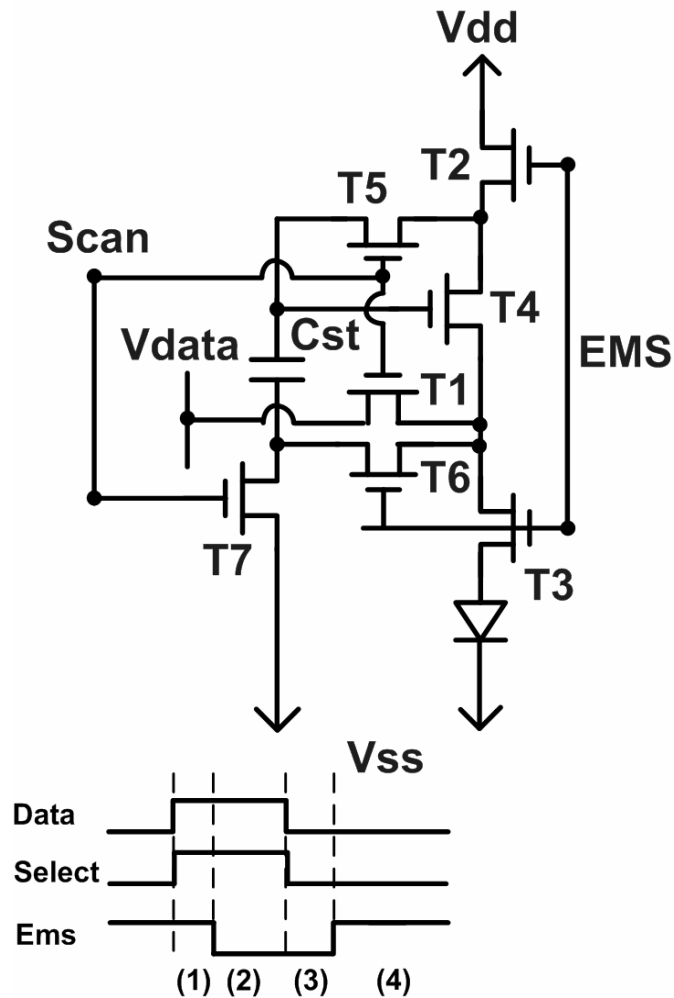


Fig. 2.4. Diode connection pixel circuit and its timing diagram.

2.3.1.3 Resistance or Active Load

For the circuit with resistor or active load, the current variation compensation resulting from electrical variation of driving transistor and OLED is compensated by resistor [2.34] or active load [2.35]. An example of pixel circuit using resistor or active load to compensate for the variation of driving transistor is shown in Fig. 2.5 [2.35]. In this circuit, T2, is an active resistor which operates only in the saturation region since the drain and source are always connected. Because the drain terminal of driving transistor T3 is connected to the

power supply line (Vdd) through the active resistor and any variation of drain current of T2 will be reflected by voltage drop across the active resistor. For example, any reduction of the current will increase the voltage at the node A ($V_A = V_{DD} - V_{AR}$ where V_{AR} is the voltage drop across the active resistor), this voltage increase will be shared by the driving transistor and OLED and a resulting high current will flow back through OLED. As a result, the circuit with an active load can adjust the device variation automatically. However, the compensation method only works when the driving TFT, T2, is biased in the linear region. This is because if the driving transistor is operated in the saturation region but not the linear region, the drain current for OLED will be equal to $I_d = \frac{1}{2} \mu C_{ox} \frac{W}{L} (V_{gs} - V_{th})^2$, and is independent of the drain voltage. Therefore, the function of the active load or resistor will be vanished completely.

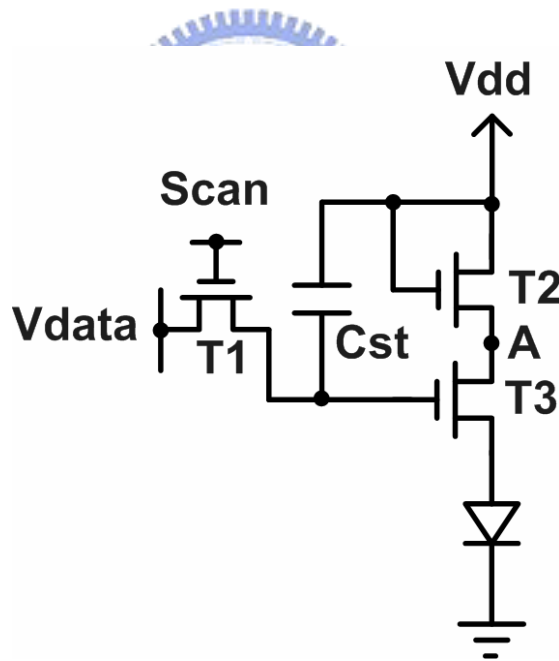


Fig. 2.5. Compensation pixel circuit by an active resistor.

2.3.1.4 Matching TFTs

In the pixel circuit which employed the concept of matching TFTs, the driving transistor is used to supply a steady current for OLED and an additional diode connected transistor is

utilized for detection of threshold voltage of the driving transistor which would be held in the storage capacitor during a frame time [2.36]-[2.37]. Fig. 2.6 shows one example of the compensation circuits by matching TFTs [2.38]. In this structure, the roles of T1 (switching TFT), T2 (driving TFT), and Cst (storage capacitor) are the same as those in the conventional circuit scheme. When the voltage of node A (V_A) is higher than that of node B (V_B), T3 turns on and T4 turns off. At this moment, the data voltage from the switching TFT is transferred to node B through T3 until V_B becomes $V_{data} - |V_{th_T3}|$. This voltage would determine the drain current of T2 and the drain current for OLED is given by the following equation while driving transistor is biased in the saturation region.

$$I_D = \frac{1}{2}k_2(V_{gs_T2} + |V_{th_T2}|)^2 = \frac{1}{2}k_2(V_{data} - |V_{th_T3}| - V_{DD} + |V_{th_T2}|)^2 = \frac{1}{2}k_2(V_{data} - V_{DD})^2,$$

$$\text{where } k_2 = \mu C_{ox} \frac{W_2}{L_2}.$$

Thus, the drain current will be independent of the threshold voltage variation of T2 with the hypothesis that the electrical characteristics of T2 and T3 are exactly the same. However, the assumption that one transistor matches another transistor completely on the same glass is very difficult to achieve in each pixel circuit.

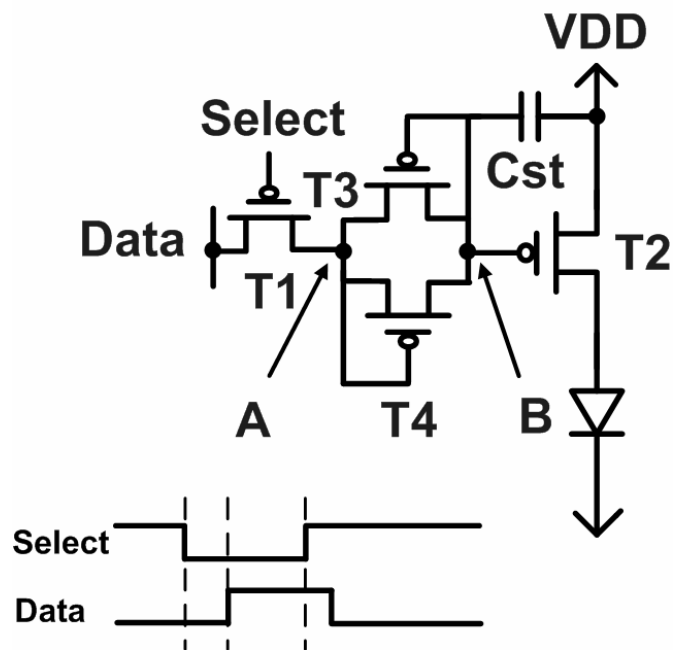


Fig. 2.6. Compensation pixel circuit by the matching TFTs with its timing diagram.

2.3.1.5 AC Driving

In the AC driving pixel circuit, a reverse-bias voltage is applied on OLED during the operation [2.39]. It is well known that the AC driving, which combines with a pulsed-driving can improve the lifetime of OLED [2.40]. When OLED device operates in the DC driving with constant current, the luminance and efficiency usually degrade gradually. This phenomenon will cause the increase of the threshold voltage of OLED. Fig. 2.7 shows the AC driving in the conventional two transistors and one capacitor (2T1C) pixel circuit [2.41]. It can be seen that a reverse voltage, V_{REV} , is connected between the cathode of OLED and the ground. If the magnitude of V_{REV} and duration of pulse voltage are both enough, the reverse voltage will be applied on OLED. During this period of V_{REV} application, the current of OLED is decreased to zero, and OLED is luminous during other period. The treatment of the reversed bias leads to improvement in J-V characteristics and thus the brightness across the panel can be improved effectively. However, this kind of pixel circuit does not take the variation between the transistors into account when AC driving is

applied on OLED.

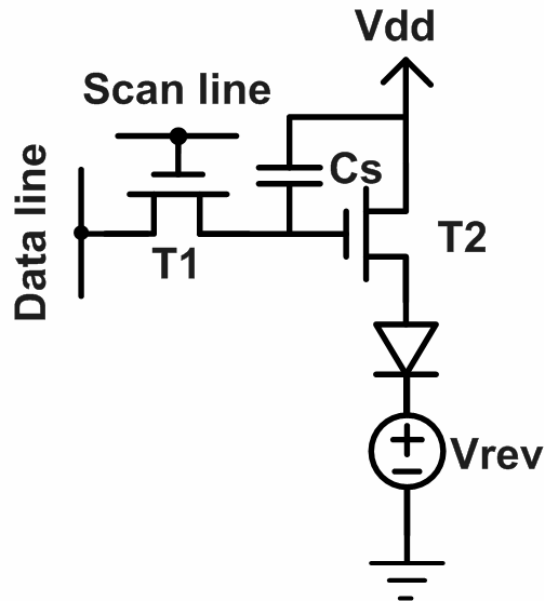


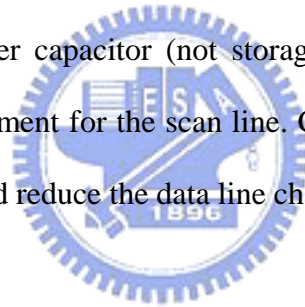
Fig. 2.7. AC driving for AMOLED.

2.3.2 Current Programmed Circuits

2.3.2.1 Current Copy

In the current programmed pixel circuits, operation mode consists of two major stages, which are the programming period and the reproduction period. A pixel is programmed with a data current first and then allowed to operate independently for the rest of the frame time. The advantage of programming the pixel with a current source is that the variation in the transistors and OLED can be calibrated out by settling the pixel to the desired current condition. An example of such pixel circuits is shown in Fig. 2.8 [2.42]. In this structure, programming the pixel is accomplished by turning on MN1 and MN3 in the addressing time. The input programming current then flows through the diode-connected driving transistor, MN2, into OLED and also charges the storage capacitor (C1) to a specified value of gate voltage required for the flow of this data current at the same time. Because the gate voltage

tracks the threshold voltage and mobility of the driving TFT, the effect of variation in electrical performance can be cancelled. During the second period, namely the reproduction period, MN1 and MN3 are turned off and the pixel is connected to the power supply line (V_{DD}) through MN4 for illumination at this time. It is supposed to reproduce the value of data current because the capacitor maintains the same gate to source voltage during the rest of the frame period. Therefore, for current copy circuits, the programming current should be the pixel current and the reproduction current has a linear relationship with the programming data current. However, the charging time of the data line capacitive load is an issue because the data current is only less than few μA . To solve the charging problem, another modified current programmable pixel circuit, which is so-called offset current copy, was proposed for large size and high resolution displays [2.43]. It works by the capacitive coupling effect through another capacitor (not storage capacitor) when the select line is deselected at the transition moment for the scan line. Consequently, the data current can be larger than the pixel current and reduce the data line charging time.



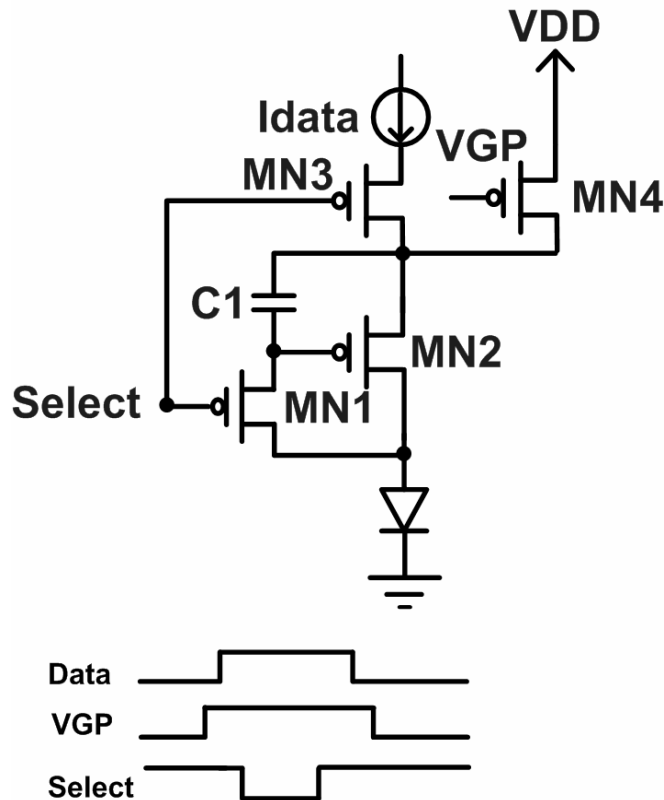


Fig. 2.8. Current programmed pixel circuit and its timing diagram.

2.3.2.2 Current Mirror

A pixel circuit employed current mirror concept is built in Fig. 2.9 [2.44] and the accomplishing circuit operation is as the following. When the write scan line and erase scan line are both selected in the programming period, the data current (I_{data}) is applied to the data line accompanied with T1 and T2 forming a current mirror. The pixel current would be equal to the programming current and the required gate to source voltage (V_{gs}) of the driving transistor T2 would be stored in the capacitor at this time. At the rest of the frame, OLED current is assumed to be the same as that in the programming period by the capability of the storage capacitor for maintaining the gate to source voltage. In addition, if defining the dimension of T1, in which the channel width is larger than that of T2, I_{data} would become larger than OLED current (I_{OLED}) As a result, the charging time will be fast enough even at low brightness. Another similar design, asymmetric- V_{dd} current mirror pixel,

was also proposed to solve the charging problem further [2.45]. However, current mirror circuits require the same characteristics in pair TFTs and this is hard to achieve.

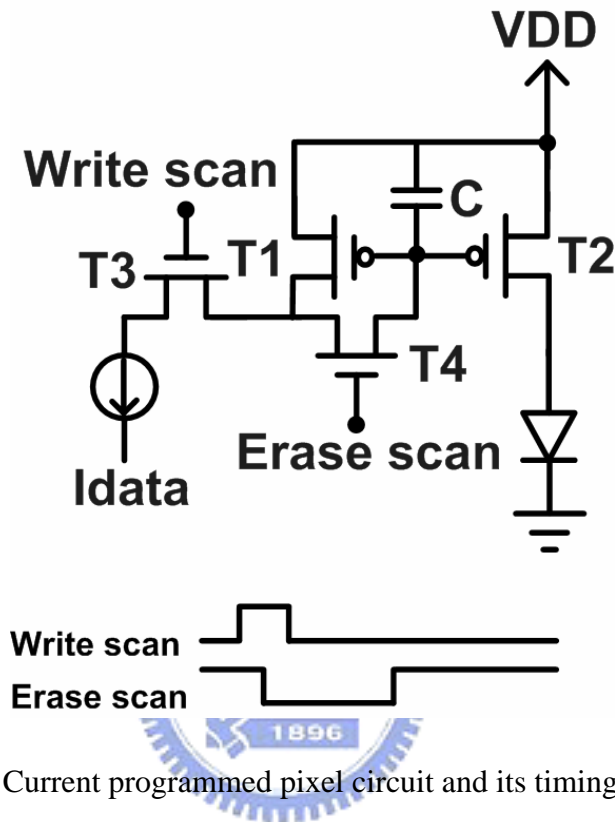


Fig. 2.9. Current programmed pixel circuit and its timing diagram.

2.3.3 Novel Driving Circuits

2.3.3.1 Clamped Inverted Driving

In the clamped inverter driving circuit, inter-pixel uniformity is achieved because each OLED is driven in the on and off states of the amplifier by the analog signal. The OLED is luminous during a period of the continuous on state and the gray scale is modulated using the applied analog signal voltage at this time. Fig. 2.10 and Fig. 2.11 show the pixel circuit configuration and its timing diagram [2.46]. In this design, OLED is connected to a CMOS inverter. During the writing period, both T1 and T2 are turned on and the analog signal and

inverter's reset voltage are applied to each node of the capacitor C1. After that, T1 and T2 are both turned off and T3 is turned on, a triangle-shaped sweep voltage is applied to the pixel. This sweep voltage travels through a whole range of the signal voltage, and the period of bright state during which OLED is luminous is controlled by a comparison between the sweep signal voltage and the signal voltage on the node of C1.

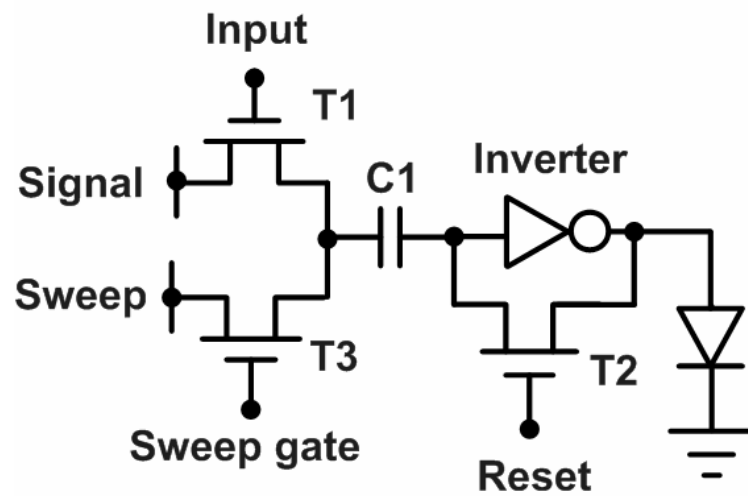


Fig. 2.10. Circuit structure of the pixel.

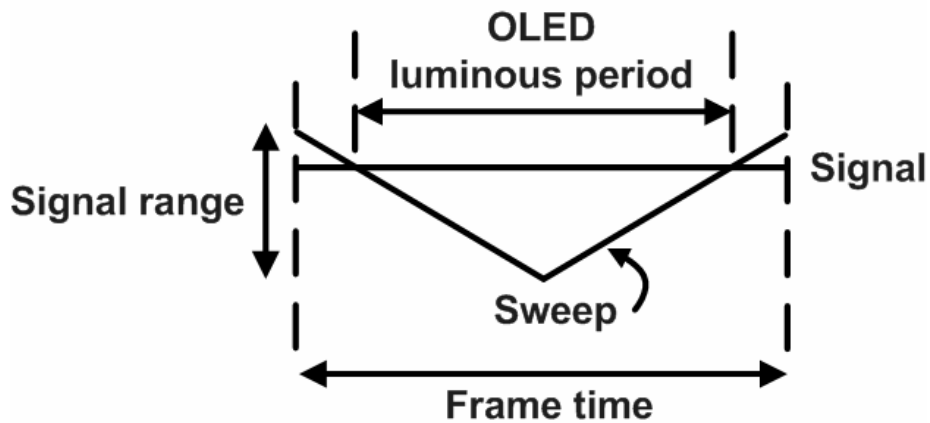


Fig. 2.11. Timing diagram of OLED driving.

2.4 Summary

All kinds of pixel circuits are introduced according to the compensation methods in the operation period. These pixel circuits are divided into three major driving modes, which are digital driving, analog driving, and novel driving. These compensation pixel circuits are necessary owing to the electrical characteristic variation of the transistors resulted from the fluctuations in excimer laser energy in the panel and each kind of circuit designs has its own advantages and disadvantages. Although digital driving methods can provide uniform image quality, they are difficult to be applied to high resolution products. Analog driving method can be classified to voltage programming circuits and current programming circuits based on the external applied signal source. Voltage programmed circuits are more attractive to integrate poly-Si TFT data drivers on the display panel. However, they can not compensate for the mobility variation of the transistors. Current programmed circuits can perform excellent image quality but they have the limitation of the writing time in the lower gray scale and the data driver IC is bigger and more expensive than a voltage driver IC. Novel driving method that is called clamped inverter driving circuit can also achieve uniform brightness across the panel by the comparison between the sweep voltage and signal voltage in order to control the duration of luminous state.