# Driving technologies for AMOLEDs

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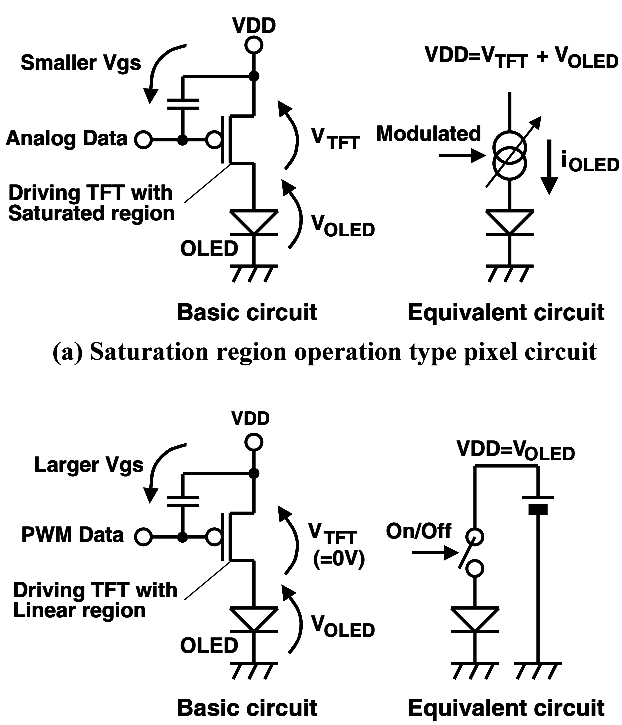
## Abstract

*This paper classifies driving technologies for AMOLEDs by the driving TFT conditions in pixels. A saturation region operation type driving TFT circuit provides good stability of OLED because of constant current drive. However, complicated compensation circuits are necessary to avoid effect of the TFT characteristics deviation. On the other hand, a linear region operation type driving TFT circuit provides better uniformity of the display image and lower power consumption. However, the stability of OLED is critical because of constant voltage drive.*

## 1. Introduction

After a fever of AMOLED (Active Matrix Organic Light Emitting Diode), finally we are starting the commercialization. Despite of strong expectation for the quick commercialization, it was a long and difficult way to reach this point. This delay originates from the critical design of pixel for AMOLED. The fact that there has still been no pixel circuit standard for AMOLED shows that it is really difficult to achieve both high performance of the display and good productivity.




**(a) Saturation region operation type pixel circuit**

**(b) Linear region operation type pixel circuit**

**Figure 1 Basic core pixel circuits for AMOLEDs**

From the background above, this paper reviews various kinds of AMOLED pixel circuits and driving methods. Especially, the driving TFT that provides the current to drive the OLED material in each pixel acts the most important role to determine the quality of the display image. We can classify the pixel circuits of AMOLED for two groups by operation condition of the driving TFT. One is a saturation region operation type pixel circuit and the other is a linear region operation type pixel circuit.

Figure 1 shows the two types of basic core pixel circuits for AMOLEDs. All AMOLEDs use one of the two circuits. Generally, an analog data signal is used to control the driving TFT gate in the saturation region operation type pixel circuit. On the other hand, PWM (Pulse Width Modulation) digital or analog data are used in the linear region operation type pixel circuit. In order to achieve longer lifetime of the display, the saturation region operation is superior to the linear region operation because the TFT on saturation region can keep the constant current even though the resistance of the OLED may be increased by the degradation of the OLED material property. However, the modulated current $i_{OLED}$ depends on the driving TFT characteristics such as Vth (Threshold Voltage) or mobility. It is very difficult to achieve extremely uniform TFT characteristics on a large glass substrate with the current TFT fabrication process technology. Therefore, complicated Vth compensation circuits are usually applied for this type to solve the problem. On the other hand, the linear region operation type pixel circuit can be escaped from the problem of TFT characteristics deviation because $V_{TFT}$, the voltage applied to the driving TFT, is negligible compared to $V_{OLED}$, the voltage applied to the OLED. Therefore, the driving TFT characteristic deviation scarcely affects the driving condition of the OLED. Moreover, the power consumption can also be decreased because the driving TFT doesn't consume power in this circuit.

## 2. Saturation region operation type pixel circuits

**Table 1 Comparison of saturation region operation type pixel circuits for AMOLEDs**

| Types of pixel circuit | Function of compensation | Number of devices | Uniformity of image (compensation) | Possibility for larger display |
|---|---|---|---|---|
| Basic circuit | No compensation | 2TFT1Cap [1] | Bad | Easy |
| Voltage programming | Neighbor TFT Vth detection | e.g. 4TFT1cap [2] | Fair (Vth only) | Easy |
| | Driving TFT Vth detection | e.g. 5TFT2Cap [4] | Good (Vth only) | Easy |
| Current programming | Real current/ Current copy | e.g. 4TFT1Cap [5-7] | Excellent (Vth and μ) | Impossible |
| | Current mirror | e.g. 4TFT1Cap [8] | Fair (Vth and μ) | Possible |
| | Voltage boost | 4TFT2Cap [9-11] | Good (Vth and μ) | Difficult |

There are three categories in this type of the pixel circuits. First method is the simplest basic 2TFT1Cap pixel circuit without Vth compensation [1]. Though it is difficult to achieve uniform image with this circuit, this simple circuit configuration realizes good productivity. Second type is a voltage programming pixel circuit. This is one of the most practical approaches to achieve both uniform image and cost competitiveness because conventional analog voltage LCD driver LSI can be applied [2-4]. The last technique is a current programming pixel circuit. Though it can achieve the widest margin for TFT characteristics, the writing speed of the pixel circuit is limited and the driver LSI chip size becomes a little larger to keep good uniformity of output current in each terminal [5-11].

### 2.1 Basic 2TFT1Cap pixel circuit

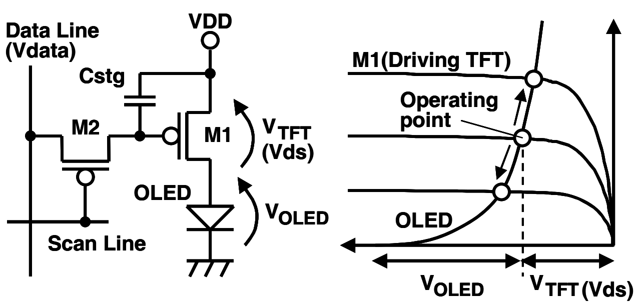



**Figure 2 Basic 2TFT1Cap pixel circuit diagram and the operation of the circuit**

Figure 2 shows a basic 2TFT1Cap pixel circuit diagram and the operation of the circuit [1]. The driving TFT is used as a current source for each color OLED. The required current for the driving TFTs to drive the OLED materials are different among three R, G, and B colors to achieve good white balance. Therefore, the optimization of the driving TFT device dimension in each color is one of the most important factors to design the pixel circuit.

### 2.2 Voltage programming pixel circuit

Function of voltage programming is to detect Vth of the driving TFT and to apply the Vth compensated data voltage to the driving TFT. Generally more than 4 TFTs are used in this pixel circuit. There are two approaches to detect the Vth of the driving TFT. One is to use a neighbor diode connected TFT [2] and the other is to detect the Vth of the driving TFT by resetting the TFT with diode connection [3,4]. The driving TFT Vth detection type is superior to the neighbor TFT diode connection type because Vth of the neighbor TFT is not exactly same as the Vth of the driving TFT.

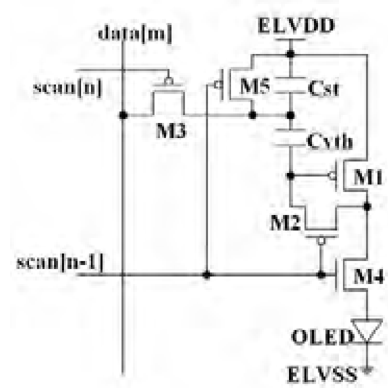



**Figure 3 5TFT2Cap Voltage programming pixel circuit configuration [4]**

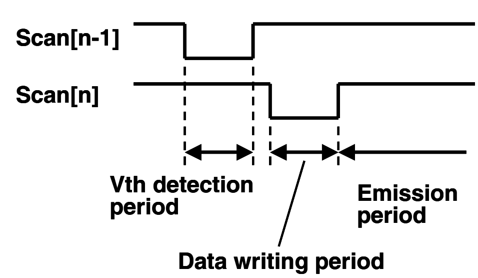
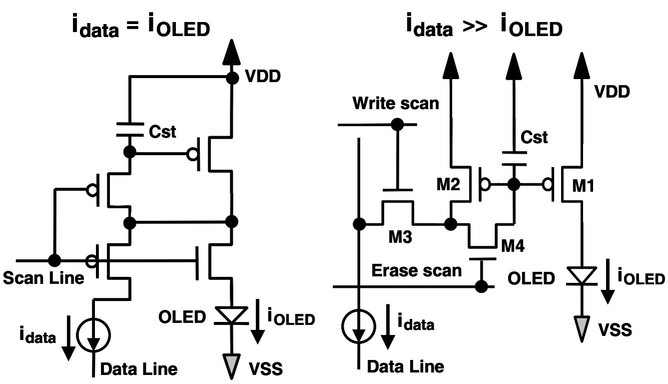



**Figure 4 Timing diagram of the 5TFT2Cap pixel circuit [4]**

Figure 3 and 4 show our own voltage programming pixel circuit diagram and the driving waveform of the circuit [4]. The pixel circuit is composed of 5 TFTs and 2 capacitors. TFT M2 is used for diode connection of TFT M1. TFT M4 prevents the current from flowing to the OLED during Vth detecting period. TFT M5 resets the charging voltage in Cst. During Vth detecting period before storing the data voltage in Cst, Vth of M1 is stored in Cvth. After this operation, the data voltage is stored in Cst. Finally, the Vth compensated data voltage is applied to the driving TFT M1. This pixel circuit can effectively eliminate the Vth deviation of the driving TFT M1. Moreover, this circuit has Cvth for the exclusive use of storing Vth, while the data voltage is stored in Cst. This configuration achieves fast writing of the data voltage. In other words, this circuit can be applicable not only for small displays but also large displays.

### 2.3 Current programming pixel circuit




**(a) Real current type [5]** **(b) Current mirror type [8]**

**Figure 5 Real current type and current mirror type pixel circuit configuration**

Advantage of current programming is special ability of the pixel circuit to compensate not only Vth but also mobility deviation of the driving TFT. Figure 5 shows basic real current type and current mirror type pixel circuits [5-8]. The value of $i_{data}$, the analog current data applied to the data line, is same as $i_{OLED}$, the current applied to the OLED, in this circuit. Though it achieves the ideal bias condition for the driving TFT, the writing time in lower gray level is very slow. Therefore, this circuit is only available for small displays with low resolution. The current mirror pixel circuit can use much larger current to drive the data line by using larger mirror ratio between the two TFT of M1 and M2. However, mismatch of the two TFT characteristics of M1 and M2 affects the uniformity of the display image.

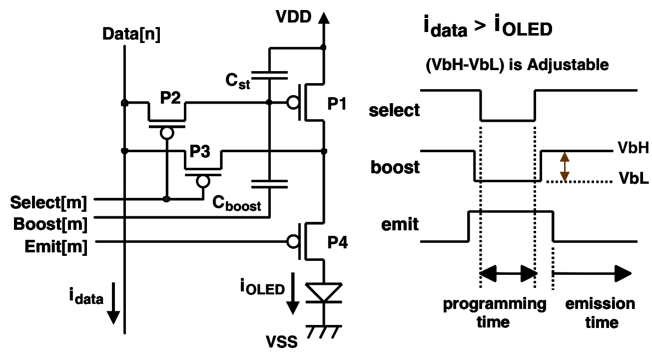



**Figure 6 Voltage boost type current programming pixel circuit and the timing chart [9-11]**

Figure 6 is our own voltage boost type current programming pixel circuit and the timing chart [9-11]. We can use a larger current for $i_{data}$ compared with $i_{OLED}$ by the boosting voltage. However, a larger boost voltage also causes an error when the operation point of the driving TFT is shifted. Therefore, we should optimize the boosted voltage to write the $i_{data}$ on the data line sufficiently in darker level of the $i_{data}$. We can achieve a good uniformity of the display image comparable to real current mode programming pixels if we keep the boosted voltage small.

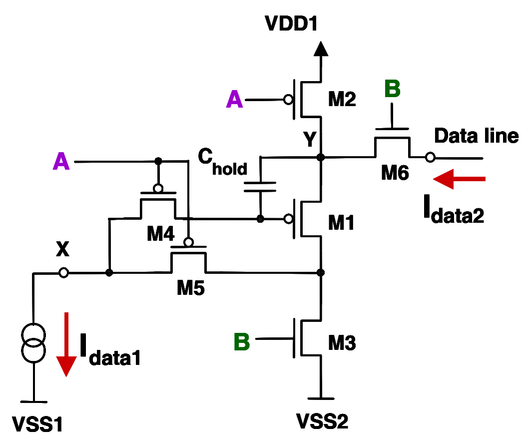



**Figure 7 Current sample and hold circuit for current de-multiplexer [10,11]**

Figure 7 shows a circuit diagram of our current sample and hold circuit. We can make current de-multiplexer circuits by combining plural of the current sample and hold circuits [10,11]. We have used a p-ch TFT for the driving TFT M1 in the current sample and hold the circuit because p-ch TFT is superior to n-ch TFT in the deviation of the TFT characteristics, flatness of the saturation region characteristics, and reliability of the device. By combining plural of the current sample and hold circuit (S/H), we are able to make a current de-multiplexer (DeMUX). Figure 8 is a circuit diagram of 1 to 3 current DeMUX with three colors rotation. This is practical enough because it has the simplest circuit structure in 1 to 3 DeMUX and all driver LSI output circuits are controlled as the

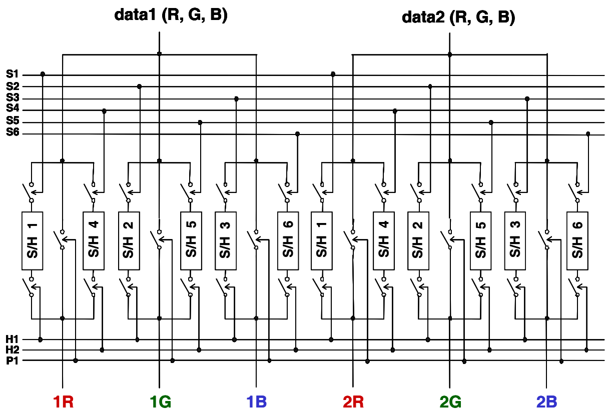



**Figure 8 Circuit diagram of 1 to 3 current DeMUX with three color rotation [10,11]**

same operation of the three colors rotation. By applying this current de-multiplexer, we are able to reduce the driver LSI output pin numbers to 1/3. Generally, voltage DeMUX can be easily applied to voltage programming AMOLEDs. Therefore, the current DeMUX is also necessary for current programming AMOLED to achieve a cost competitive display module.

### 2.4 Amorphous Silicon pixel circuit for AMOLEDs

Above discussion has been based on LTPS (Low Temperature Polycrystalline Silicon) TFTs. Basically all of the above pixel circuits are also applicable for a-Si (Amorphous Silicon) TFTs. Connection of the

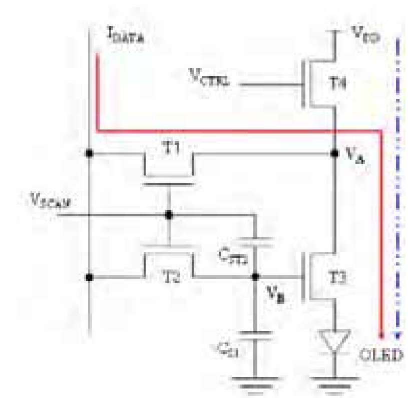



**Figure 9 Voltage boost current programming a-Si TFT pixel circuit for AMOLEDs [12]**

storage capacitor are only difference between LTPS and a-Si TFT in the circuit. In case of a-Si TFT circuit, VDD is not available for the connection of storage capacitor because only N-channel is available for a-Si TFTs. Generally, the fast degradation of a-Si TFT characteristics strongly affects the lifetime of the OLED display. Therefore, it is very difficult to achieve stable and reliable AMOLED display by using a-Si TFTs. In order to get better stability, current programming pixel circuit is more desirable than voltage programming pixel circuit especially in a-Si TFTs because only current programming pixel circuit can compensate both Vth shift and degradation of the driving TFT mobolity.

Figure 9 is an example of a-Si TFT pixel circuit for AMOLED [12]. This circuit is basically same as our voltage boost current programming pixel circuit in Fig. 6. This circuit has limited boost voltage range and timing because the boost capacitor control line is not independent of the scan line.

## 3. Linear region operation type pixel circuits

**Table 2 Comparison of linear region operation type pixel circuits for AMOLEDs**

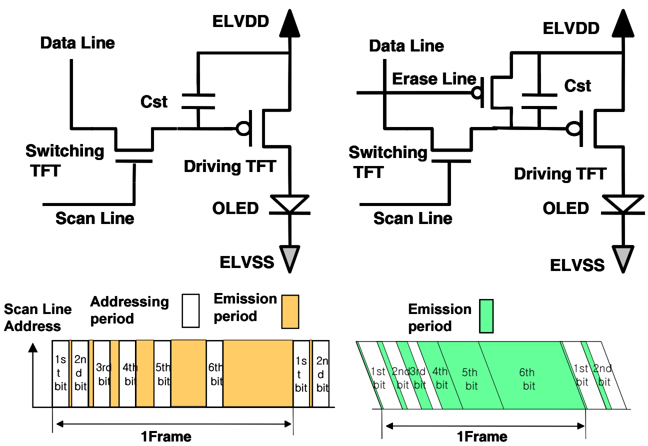
| Types of Pixel circuit | Gray scale modulation | Number of Devices | Advantage | Disadvantage |
|---|---|---|---|---|
| Digital area modulation [13] | Binary weighted sub aperture | 2TFT1Cap x n-bit | Low frequency | Limited gray level |
| Digital PWM | DPS* [14] | 2TFT1Cap (Simplest) | Highest Aperture ratio | Highest frequency |
| | SES** [15] | 3TFT1Cap | High Aperture ratio | Higher frequency |
| | MAS*** [16,17] | 2TFT1Cap (Simplest) | Highest Aperture ratio | High frequency |
| Ramp wave Controlled PWM (Analog) | Comparator [18] | 4TFT3Cap | No false contour Low frequency | Lower Aperture ratio |
| | Clamped Inverter [19] | 4TFT1Cap | No false contour Low frequency | Low Aperture ratio |

DPS*: Display Period Separated driving method
SES**: Simultaneous Erase Scan driving method
MAS***: Multiple Addressing Scan driving method

Table 2 shows the comparison among linear region operation type pixel circuits. There are three categories. First method is a digital area modulation [13]. Although it is easy to get good uniformity and linearity of gray scale, gray scale level is limited. Second type is a digital PWM method that is similar to the driving method of PDP display [14-17]. This method can achieve the highest aperture ratio of the pixel, the widest margin for TFT characteristic deviation, and sufficient gray scale numbers. However, the driving method is complicated and the data frequency is also high. The last pixel circuit type is a ramp wave controlled PWM method [18,19]. Although it is not suffered from false contour problem that is essential to the digital PWM method, the pixel circuit is a little complicated.

### 3.1 Digital PWM driving method

There are three types of digital PWM drive methods. Basic two methods of them are shown in Fig. 10. DPS (Display Period Separated) driving method emits a sub-frame display image of whole screen simultaneously after all data have been written [14].




(a) DPS driving method (b) SES driving method

**Figure 10 Typical digital PWM driving methods and pixel circuits for AMOLEDs [14,15]**

This is similar to the driving method of PDP displays. The addressing period is not available for emission in this scheme. In order to minimize the loss time for emission, SES (Simultaneous Erase Scan) method can erase the sub-frame image before the addressing has been finished [15]. Therefore, the loss time for emission is shorter than that of DPS driving method. MAS (Multiple Addressing Scan) method can completely remove the loss time for emission [16,17]. However, the driving scheme is complicated because the order of the image data must be re-arranged to achieve the special scan of the method. The combination of the MAS method and saturation region operation type pixel TFT circuit has also been reported [17].

### 3.2 Ramp wave drive pixel circuit

Digital PWM forces human eyes to average separated sub-frame emission periods to notify original analog gray scale. On the other hand, ramp wave drive pixel circuit can avoid the separate emission period. Therefore, essential problem of digital PWM such as false contour or flicker is not recognized in this method. There are two types of ramp wave drive

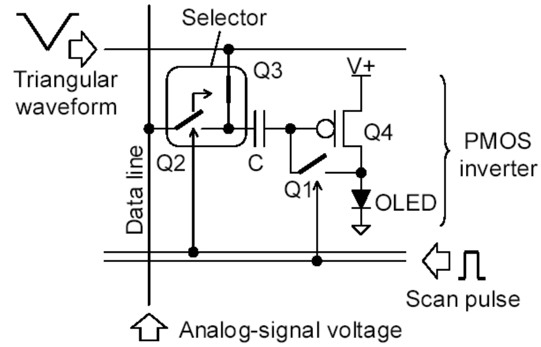



**Figure 11 Clamped inverter type pixel circuit [19]**

pixel circuits. One is a comparator type pixel circuit [18] and the other is a clamped inverter type pixel circuit [19]. Figure 11 is a circuit diagram and driving waveform of the clamped inverter pixel circuit. The Vth deviation of the PMOS inverter TFT doesn't affect the modulated emission period in this circuit because Vth of the TFT is detected and compensated when the selector applies the analog data voltage to the PMOS inverter.

## 4. Conclusion

We have reviewed various kinds of AMOLED pixel circuits and driving methods. We have classified the pixel circuits into two groups by focusing the driving TFT operation mode because the driving TFT acts the most important role to determine the image quality of the AMOLED display.

Saturation region operation type driving TFT circuit provides good stability of OLED because of constant current drive. However, complicated compensation circuits are necessary to avoid affection of the TFT characteristics deviation. Voltage programming and current programming are available for the compensation. Although the current programming has better compensation ability than voltage programming, the slow speed of the data writing is critical for the panel design and practical driver LSI development is also difficult.

On the other hand, linear region operation type driving TFT circuit provides better uniformity of the display image and lower power consumption. However, the stability of OLED is critical because of constant voltage drive. Digital PWM drive can achieve the highest aperture ratio that is suitable for higher resolution displays. Ramp wave controlled PWM also has a possibility to realize better image quality than digital PWM. We believe that the drastic improvement of the stability of OLED materials will enable us to apply the linear region operation type driving TFT circuit for AMOLED in the near future.

## 5. Acknowledgements

We are grateful to Mr. N. Komiya and AMOLED business team engineers for fruitful technical discussion and support. We also thank to Mr. D. Y. Shin in Seoul National University for circuit design and simulation of our AMOLED display.

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