

## 3.5 Proposed Pixel Circuit Design

In this section, two new voltage programming pixel circuits which consist of five poly-Si thin film transistors, a storage capacitor and one additional control signal were developed. The simulation and experimental results show that the pixel design is capable of reducing the non-uniformity of brightness and possessing larger output current.

### 3.5.1 Compensation Method Using Diode Connection

#### Concept



In the diode connection compensation circuit, the fundamental design of a pixel which compensates for the threshold voltage variation needs another transistor as a switch to form diode-connection and passing data voltage during the writing or programming period [3.47]-[3.48]. Fig. 3-21 shows the compensation examples by diode connection of the n channel TFT circuit and p channel TFT circuit in the programming period. It is clear that  $V_{data}$  turns into  $V_{data}+V_{th}$  in the gate terminal of the n type driving transistor diode connection while it turns into  $V_{data}-|V_{th}|$  in the gate terminal of the p type driving transistor diode connection. Since the driving current of OLED in n type driving TFT is affected by the threshold voltage of OLED, while p type driving TFT is affected by the voltage drop from the power supply. From our previous experience in OLED real panels, the voltage drop from the power supply is the tough and serious problem than OLED threshold voltage deviation. Therefore, n

type driving TFT is adopted in our pixel design.

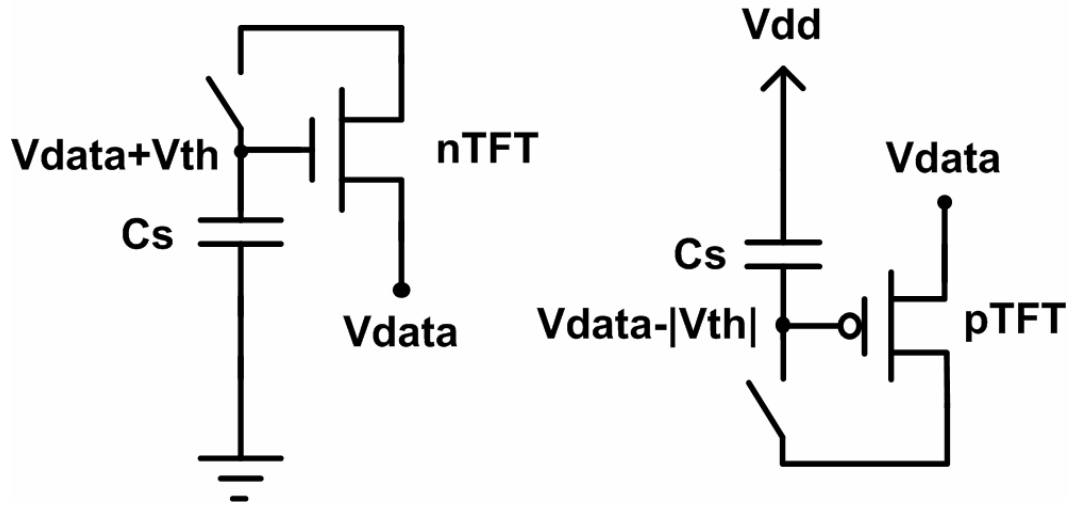


Fig. 3-21. Examples of compensation by diode connection in the n type TFT circuit and p type TFT circuit.

### 3.5.2 Simulation Results and Discussion



Fig. 3-22 shows the transient response of conventional 2T1C pixel circuit. In this case the threshold voltage deviation of LTPS TFTs is assumed to be 0.33 volt. It is observed that the anode voltage of OLED is dependent on the threshold voltage variation and the non-uniform image quality across the display is produced. Fig. 3-23 shows the proposed pixel structure and the signal driving scheme, respectively. TFT1, TFT3, TFT4, and TFT5 are switching TFTs and TFT2 is a driving TFT. The operation scheme and compensation principle are divided into three stages and described as follows:

**1. Initialization period:** During the first period, reset action is performed. Vsel and Vctrl signals are high voltages, all TFTs in this pixel are turned on. The previous stored voltage in the Cs would be charged up to a specific value.

**2. Data input period:** Vctrl signal is low, turning off TFT4 and TFT5 for storing the threshold voltage of driving transistor (TFT2). At this time, the gate terminal of TFT2 is connected with the drain terminal by TFT3. Because TFT2 acts as a diode connection, Vgs is Vth\_T2 and stored voltage across the capacitor is Vdata + Vth\_T2.

**3. Emission period:** After scanning time and signal sampling stage, Vsel is low and Vctrl is high. During this period, driving TFT (TFT2) starts to drive OLED, and the stored voltage in Cs would maintain until the next reset period. The drain current of TFT2 in the saturation region for OLED becomes as follows:

$$\begin{aligned}
 I_{OLED} &= \frac{1}{2}k_2(V_{gs\_T2} - V_{th\_T2})^2 \\
 &= \frac{1}{2}k_2(V_{data} + V_{th\_T2} - V_{th\_T2})^2 = \frac{1}{2}k_2V_{data}^2 \dots\dots\dots (3.2)
 \end{aligned}$$

Therefore, the drain current of TFT2 is independent of the threshold voltage of TFT2, and only affected by Vdata, the pixel-to-pixel threshold voltage variations can be compensated effectively and uniform brightness image performance can be achieved. Compared with conventional 2T1C pixel circuit, the transient response of the proposed pixel circuit shows much consistence of driving current against the threshold voltage variation as shown in Fig. 3-24. It is demonstrated that the anodes of OLED devices are insensitive to different threshold voltages. The difference of the stored voltage in the capacitor almost equals the difference of threshold voltage in driving transistor as shown in Fig. 3-25.

In order to study the effect of the device variation on the conventional and proposed circuit design, the Monte Carlo simulation with an assumption of normal distribution was also executed in the following sections. The mean value and the deviation of the threshold voltage and mobility are 1.55V, ± 1V, 52.02 cm<sup>2</sup>/V-s, and ± 20 cm<sup>2</sup>/V-s, respectively, which is serious situation in device variation. Fig. 3-26 and Fig. 3-27 show the comparison of 30 times Monte Carlo simulation results of the

conventional pixel design and the proposed pixel design. From the simulation results, it is observed that the smaller current variation can be achieved in the proposed circuit obviously. The maximum variation of output current of the conventional design is  $0.029 \mu\text{A}$  between thirty set results, while that of the proposed circuit design is only  $0.0023 \mu\text{A}$ . The threshold voltage compensation for LTPS TFT can be obtained in the proposed circuit design. The device simulation parameters used in the proposed circuit design are summarized in Table 3-1.

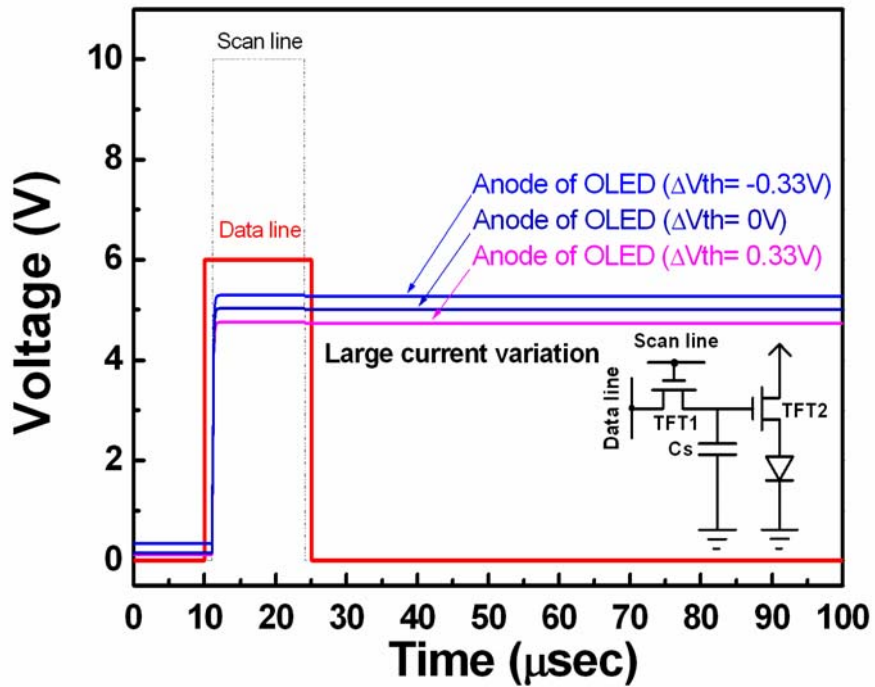


Fig.3-22. Transient response of the conventional 2T1C pixel circuit.

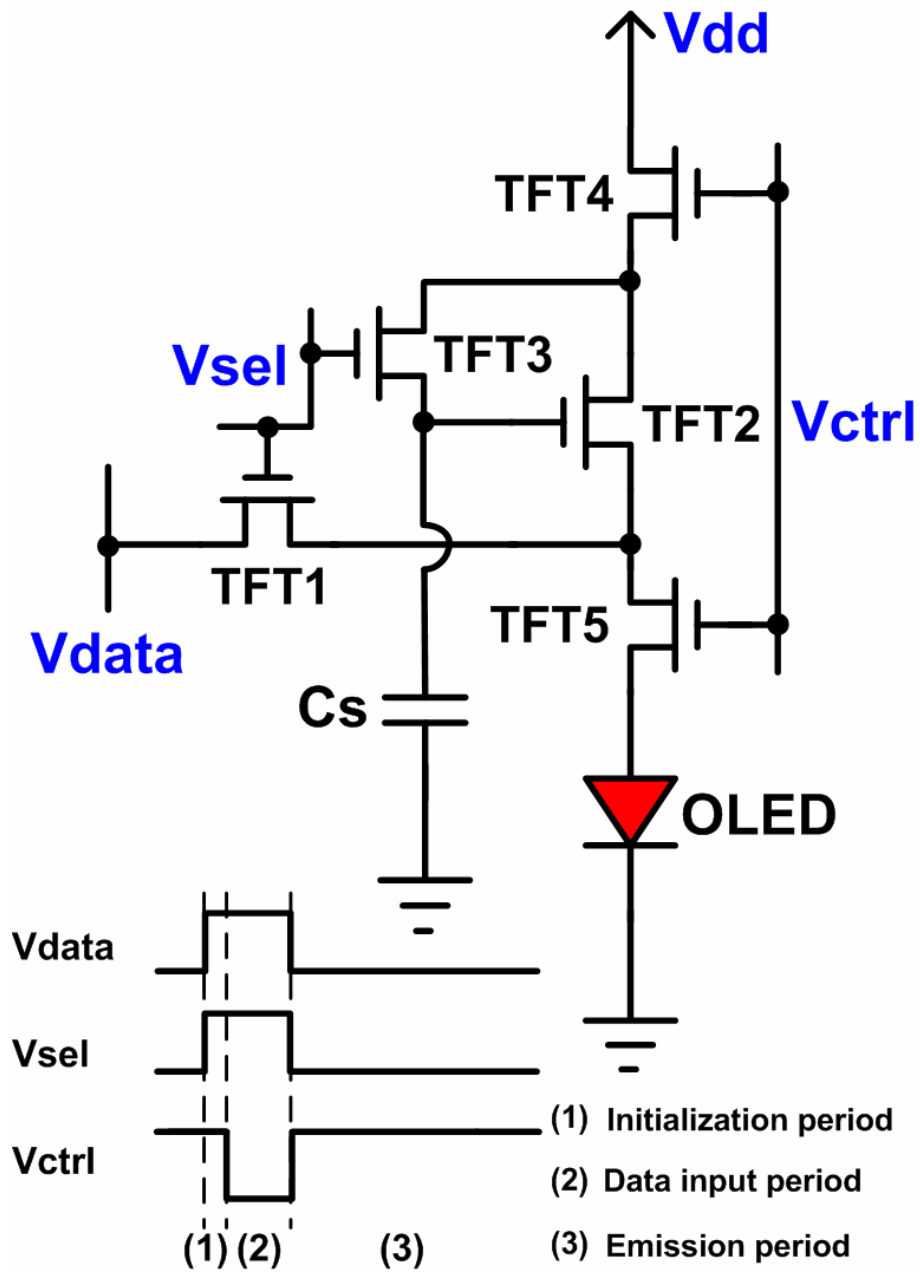


Fig. 3-23. Proposed circuit schematic and driving signals of voltage compensation circuit for AMOLED.

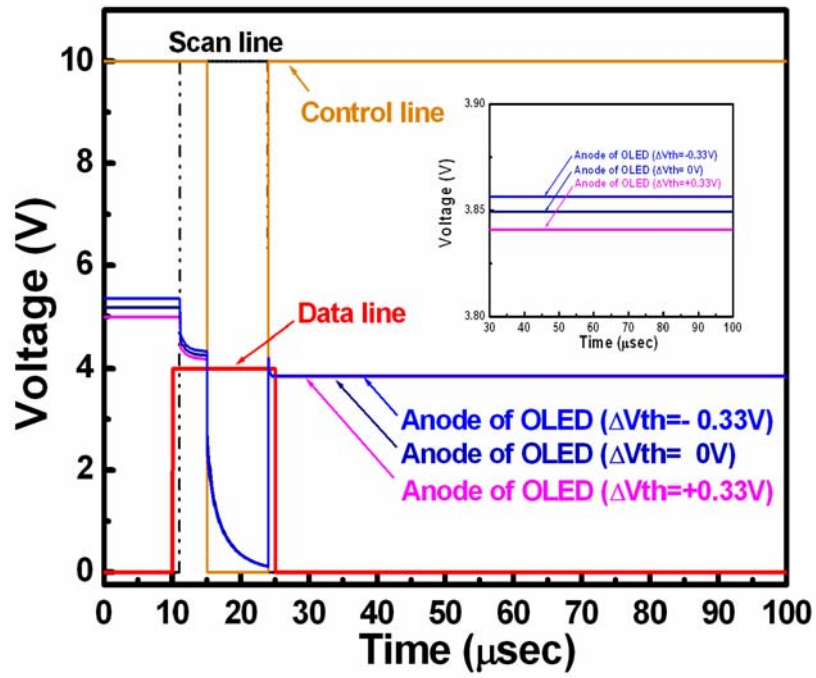


Fig. 3-24. Transient response of the proposed pixel circuit.

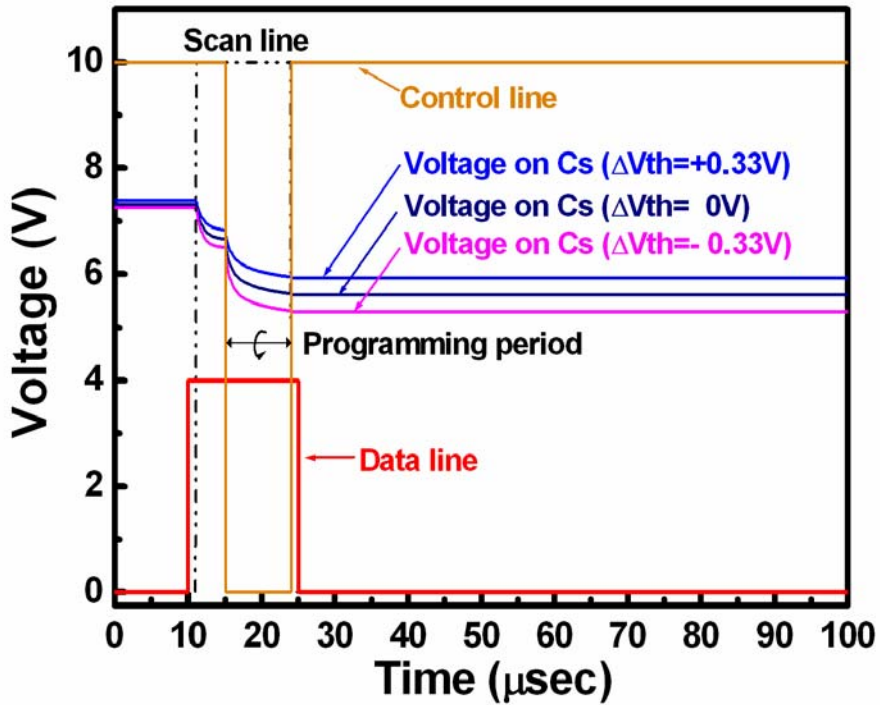


Fig. 3-25. An example of driving scheme for the stored data voltage in the capacitor with varied threshold voltages of TFTs.

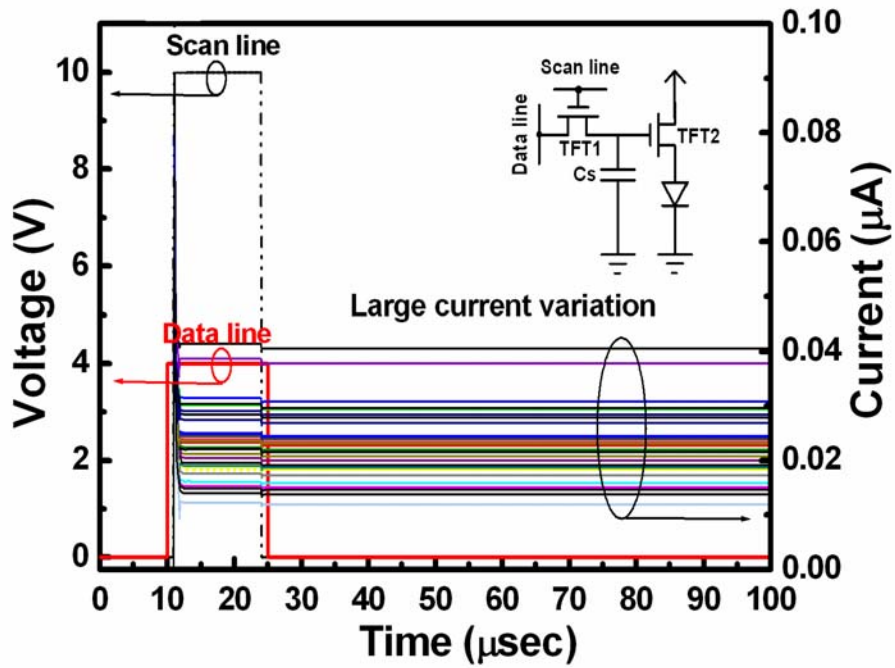


Fig. 3-26. Thirty times Monte Carlo simulation results of conventional pixel circuit.

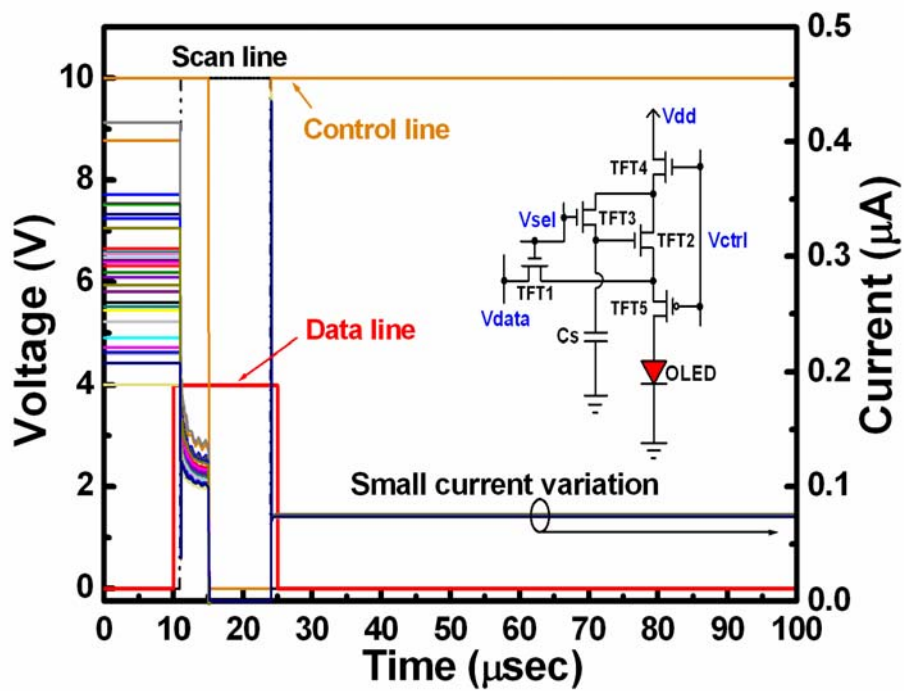


Fig. 3-27. Thirty times Monte Carlo simulation results of proposed pixel circuit.

Devices	TFT1 、 TFT3 、 TFT4 、 TFT5	TFT2	Cs
	6 $\mu\text{m}/6 \mu\text{m}$	80 $\mu\text{m}/6 \mu\text{m}$	1pF
Signals	Vdd	Vctrl, Vsel	
	10V	0V~10V	
Timing Period	Reset Period T1	Data Period T2	Emission Period T3
	5 $\mu\text{sec}$	10 $\mu\text{sec}$	85 $\mu\text{sec}$

Table 3-1. Timing period and device parameters of proposed pixel circuit simulation.

### 3.6 Modified Pixel Circuit Design

In the transient results of Fig 3-24, there is still current flowing OLED in the reset period. In order to reduce power consumption and eliminate the current flow through OLED during the reset period, a p-channel TFT5 is used to block the emission current through OLED. The measured and the simulated transfer characteristics of p channel TFT shown in Fig. 3-28. Fig. 3-29 shows the proposed pixel structure modifying previous  $\mu$  pixel circuit with the signal driving scheme. Five TFTs and a capacitor compose of this pixel circuit. TFT1, TFT3, TFT4, and TFT5 are switching TFTs and TFT2 is a driving TFT. The operation scheme and the compensation principle are described as follows:

**1. Initialization period:** In the first period, Vsel and Vctrl signals go to high voltage, TFT1, TFT3 and TFT4 are turned on consequently. The previous stored voltage in the Cs is reset to a specific value related to the following data signal; that is, initialization period.

**2. Data input period:** Switching transistors TFT1, TFT2, and TFT3 are active and TFT4 and TFT5 are turned off.  $V_{\text{data}}+V_{\text{th\_T2}}$  is stored in Cs during the second period



since TFT2 is diode connection.

**3. Emission period:** Then TFT4 and TFT5 are turned on during this period; OLED begins to emit corresponding light. The drain current of TFT2 in the saturation region becomes as follows:

$$\begin{aligned}
 I_{OLED} &= \frac{1}{2}k_2(V_{gs\_T2} - V_{th\_T2})^2 \\
 &= \frac{1}{2}k_2(V_{data} + V_{th\_T2} - V_{th\_T2})^2 = \frac{1}{2}k_2V_{data}^2 \dots\dots\dots (3.3)
 \end{aligned}$$

Therefore, the drain current of TFT2 is independent of the threshold voltage of TFT2, and only affected by Vdata. The pixel-to-pixel threshold voltage variations can be compensated effectively and more uniform brightness image performance can be achieved.

Compared with conventional 2T1C pixel circuit, the new pixel circuit shows much consistence of driving current against threshold voltage variation in Fig. 3-30. It is demonstrated that the anodes of OLED devices are insensitive to different threshold voltages. Fig. 3-31 also verifies that the modulated data voltage is stored in the capacitor as the threshold voltages of TFTs are varied. The difference of the stored voltage in the capacitor almost equals the difference of threshold voltage in driving transistor.

Fig. 3-32 shows the non-uniformity of output current of an OLED simulated with combined Vth variation ( $\Delta V_{th} = -0.33V, 0V, \text{ and } +0.33V$ ) of poly-Si TFT during programming. The non-uniformity here is defined as the difference between maximum current and minimum current, divided by the average output current. It is clear that the proposed circuit can compensate the non-uniformity of output current of an OLED effectively.

Fig. 3-33 shows the transfer characteristics of the pixel circuit at different Vdata with threshold voltage variation ( $\Delta V_{th} = -0.33V, 0V, \text{ and } +0.33V$ ). It shows that the

output current of OLED is nearly independent of threshold voltage deviation for different input data signal. Our simulation results are plotted in Fig. 3-34. The output current errors of conventional pixel circuit are all above 20% when input data voltage ranges 0.5V to 5V, which is below 3% in our proposed pixel circuit, which is shown in Fig. 3-34.

Since the modified circuit can block the current flow through TFT5 and OLED from the transient result shown in Fig. 3-30, the power reduction can further be obtained through simulation results. Fig. 3-35 shows the power reduction of the modified circuit design compared with the first one. It is obvious that power consumption can be reduced exactly even in the single pixel circuit.

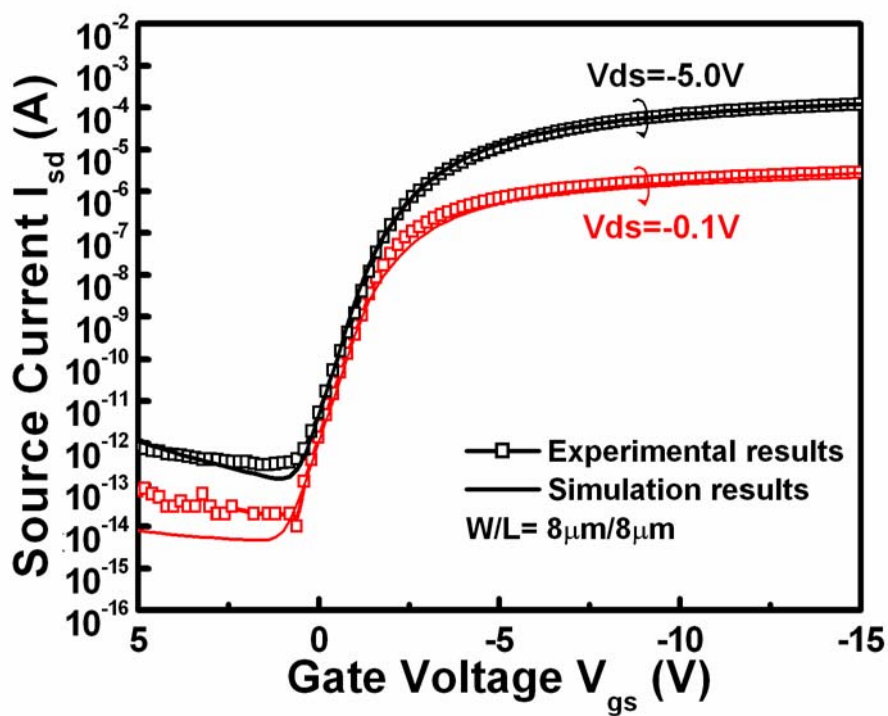


Fig. 3-28. The measured and simulated transfer characteristics of p channel TFT.

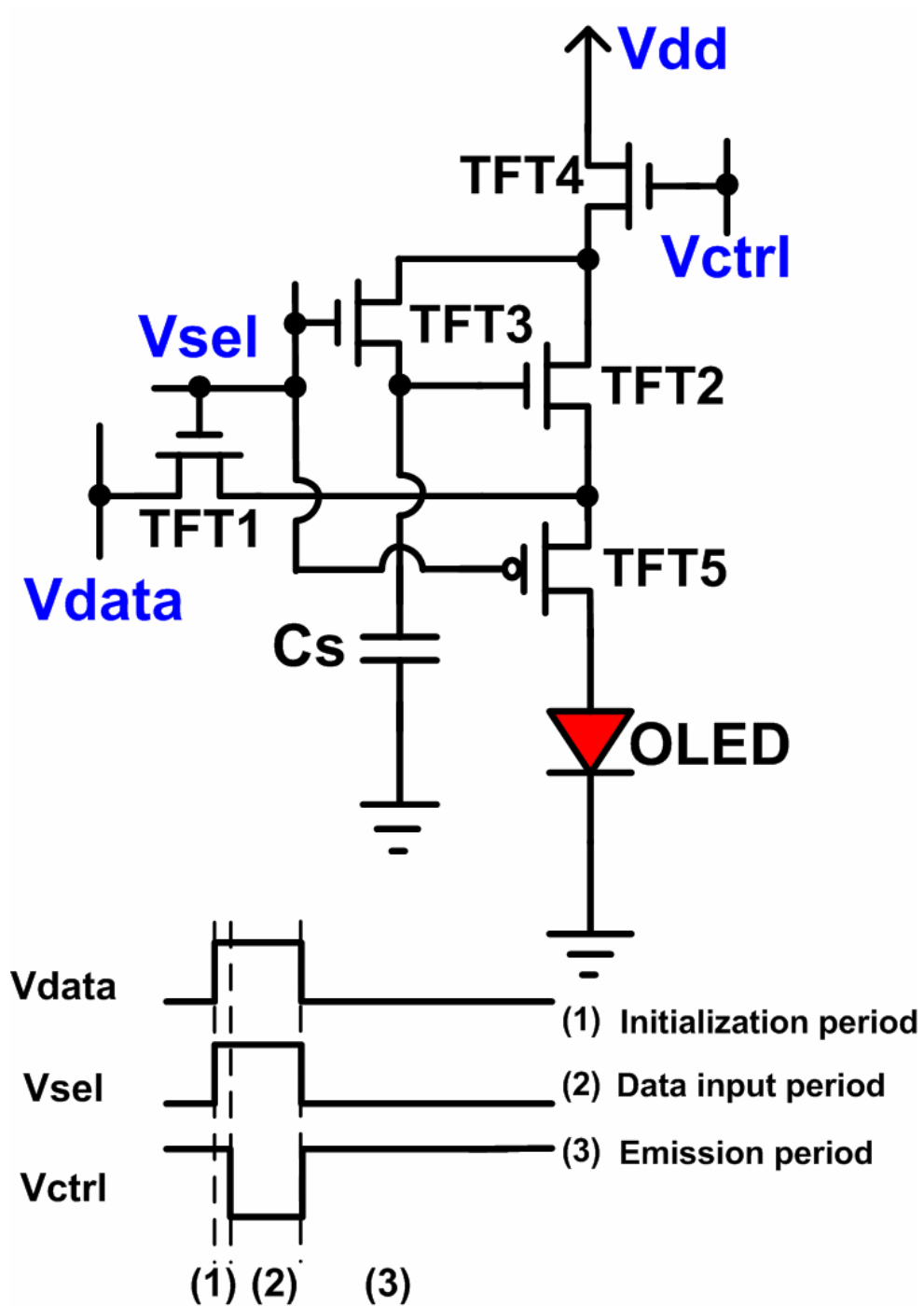


Fig. 3-29. Modified pixel circuit schematic and the timing diagram of control signals.

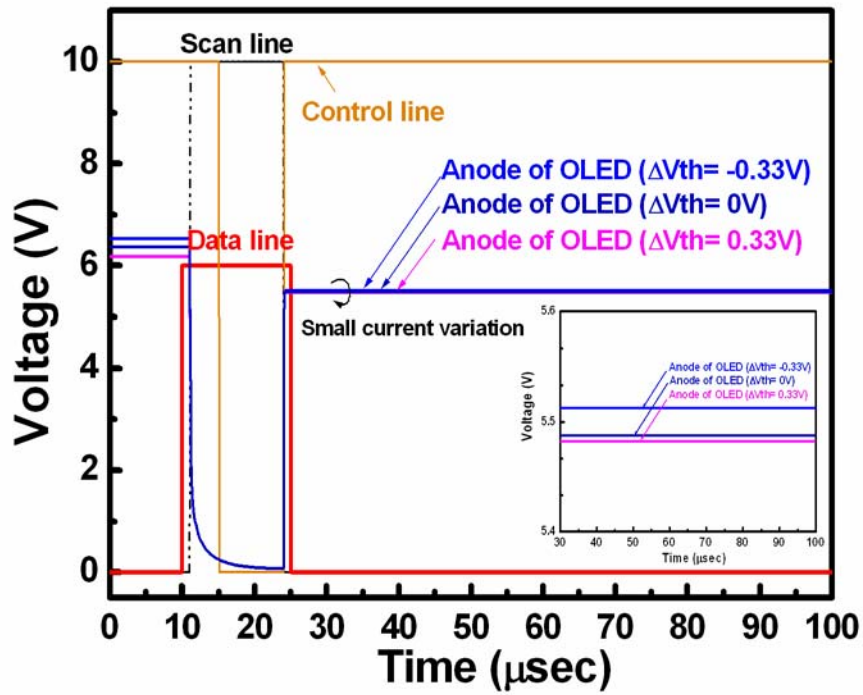


Fig. 3-30. Transient response of the modified pixel circuit.

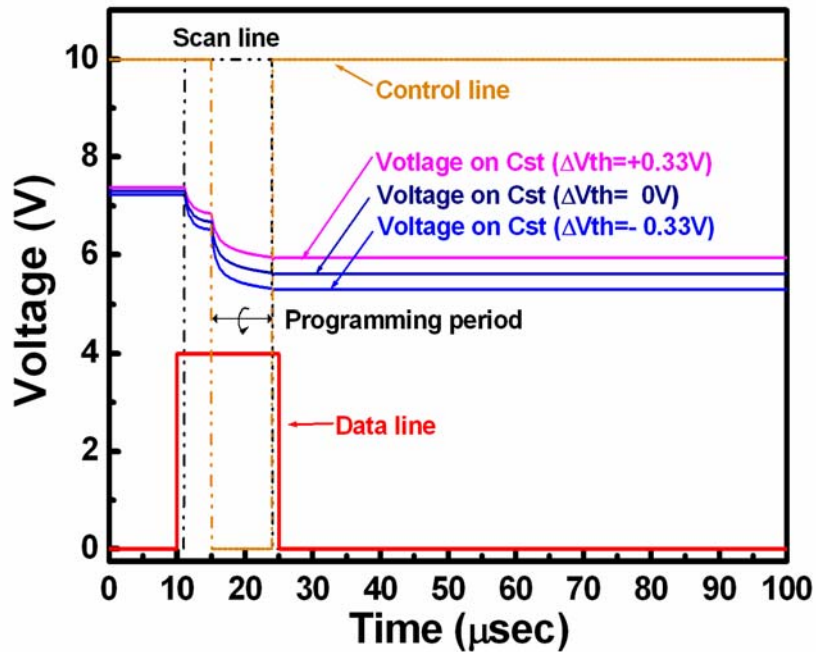


Fig. 3-31. An example of driving scheme for the stored data voltage in the capacitor with varied threshold voltages of TFTs in the modified pixel circuit.

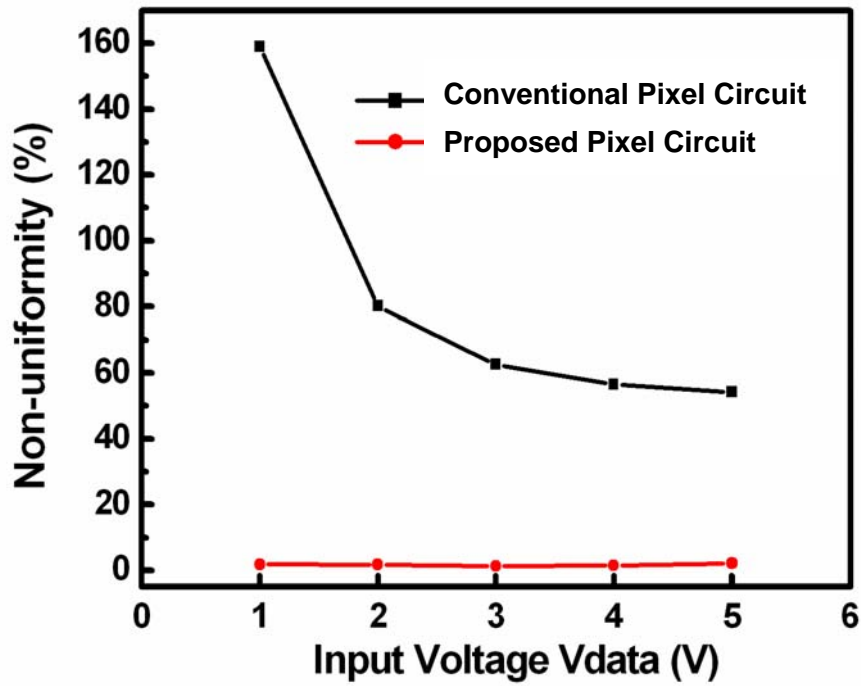


Fig. 3-32. Comparison of the output current non-uniformity.

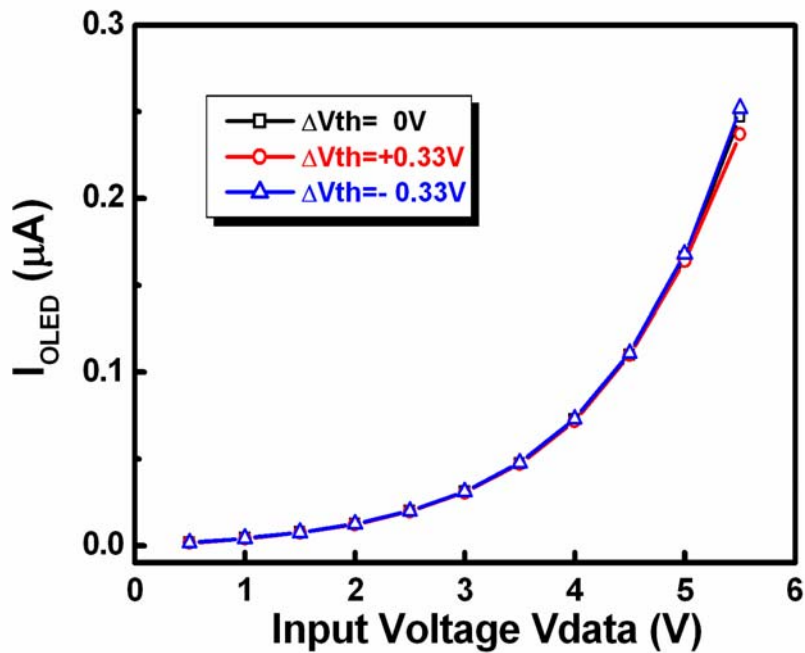


Fig. 3-33. Simulation results showing the range of current flowing through the OLED at different Vdata and threshold voltage variation ( $\Delta V_{th} = -0.33V$ ,  $0V$ , and  $+0.33V$ ).

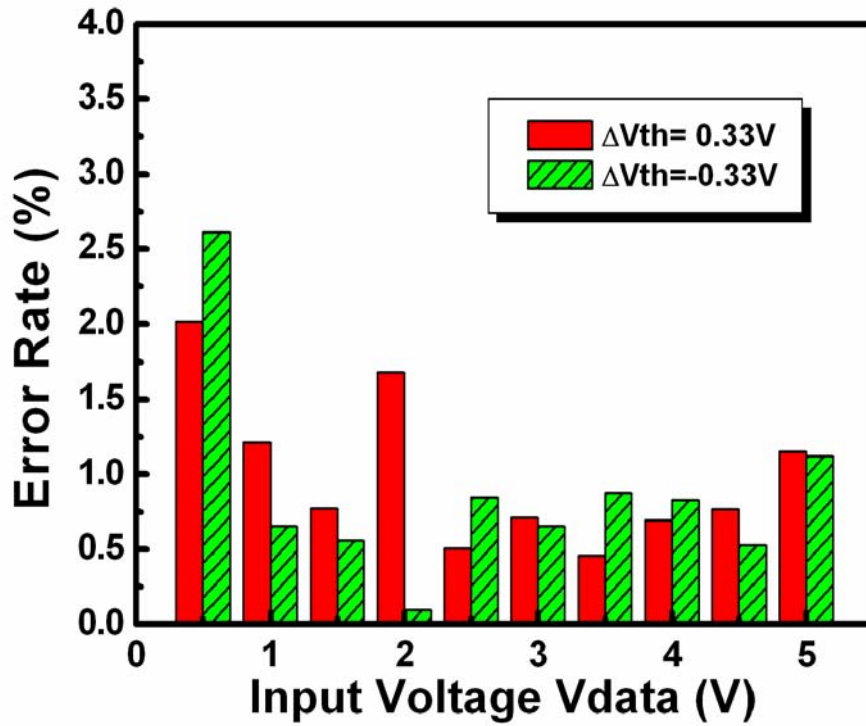


Fig. 3-34. The error rate of output current in our proposed pixel circuit.

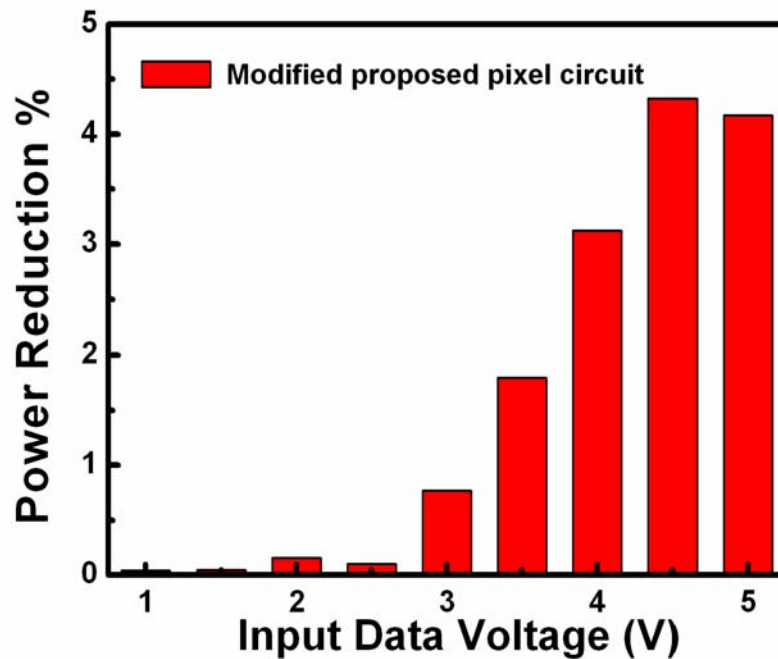


Fig. 3-35. Power reduction of the modified circuit design compared with the first one.

### 3.7 Comparison between the Proposed Pixel Circuits and Other Pixel Circuits Design

Performance like non-uniformity and power consumption of the conventional pixel design, proposed two pixel circuits, and Lee's pixel circuit [3.31] are compared to each other. Seven transistors and one capacitor comprise of Lee's pixel circuit. Among these pixel designs, our proposed pixel circuits show a significant improvement in Fig. 3-36, which indicated the non-uniformity of the output current for  $\pm 0.33V$  threshold voltage fluctuations. Power dissipation of our circuit designs for different input data voltages is shown in Fig. 3-37. By means of reducing transistors, power consumption already reduced effectively compared with the Lee's pixel design.

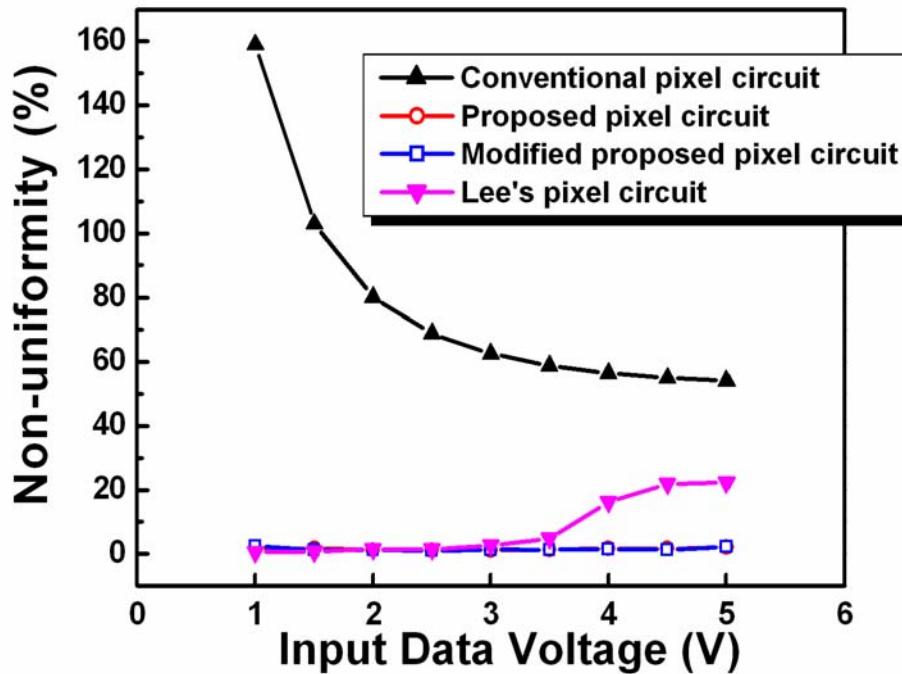


Fig. 3-36. Non-uniformity of the output current for  $\pm 0.33V$  threshold voltage fluctuations.

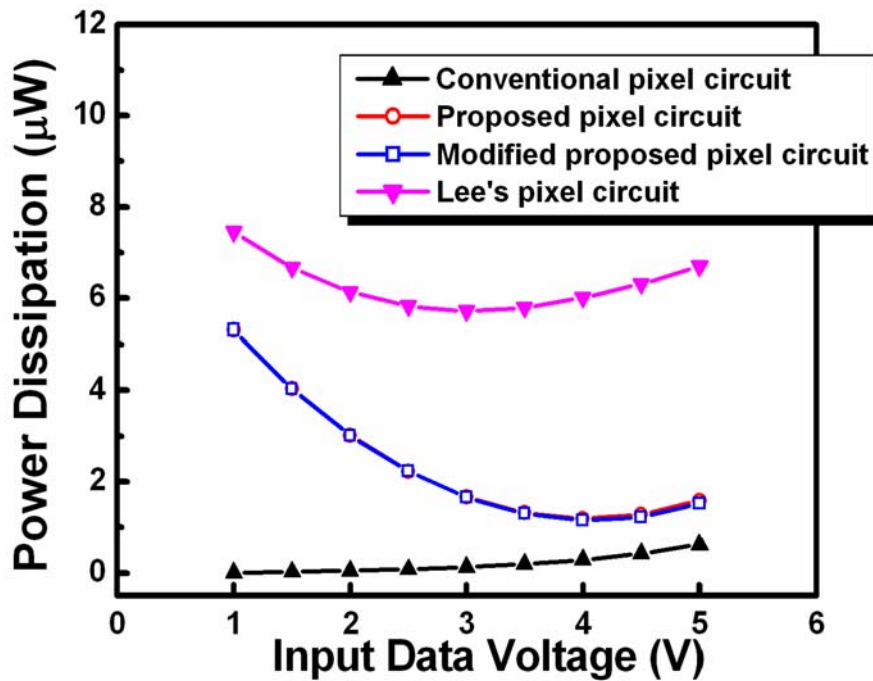
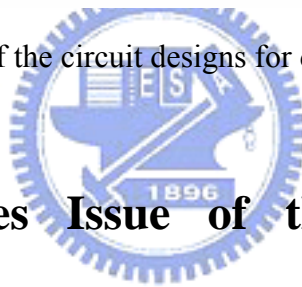


Fig. 3-37. Power dissipation of the circuit designs for different input data voltages.



### 3.8 Several-Frames Issue of the Proposed Pixel Circuit

Approaching real condition of the proposed pixel circuit applied in products is investigated which is operated in several frames in this section. Different input data voltage is assumed and simulated in the proposed pixel circuit with Monte Carlo simulation. The average value and the deviation value of the threshold voltage and mobility are assumed 1.55V,  $\pm 1V$ , 52.02  $\text{cm}^2/\text{V}\cdot\text{s}$ , and  $\pm 20 \text{ cm}^2/\text{V}\cdot\text{s}$ , respectively. For example, the data voltage are 3V, 3.5V, 1V, 2V and the variations of the proposed circuit simulation with different data voltages are shown in Fig. 3-38. Only when the data voltage, 3.5V, reveals large current variation about 4.4nA seems acceptable when applying to the real products.



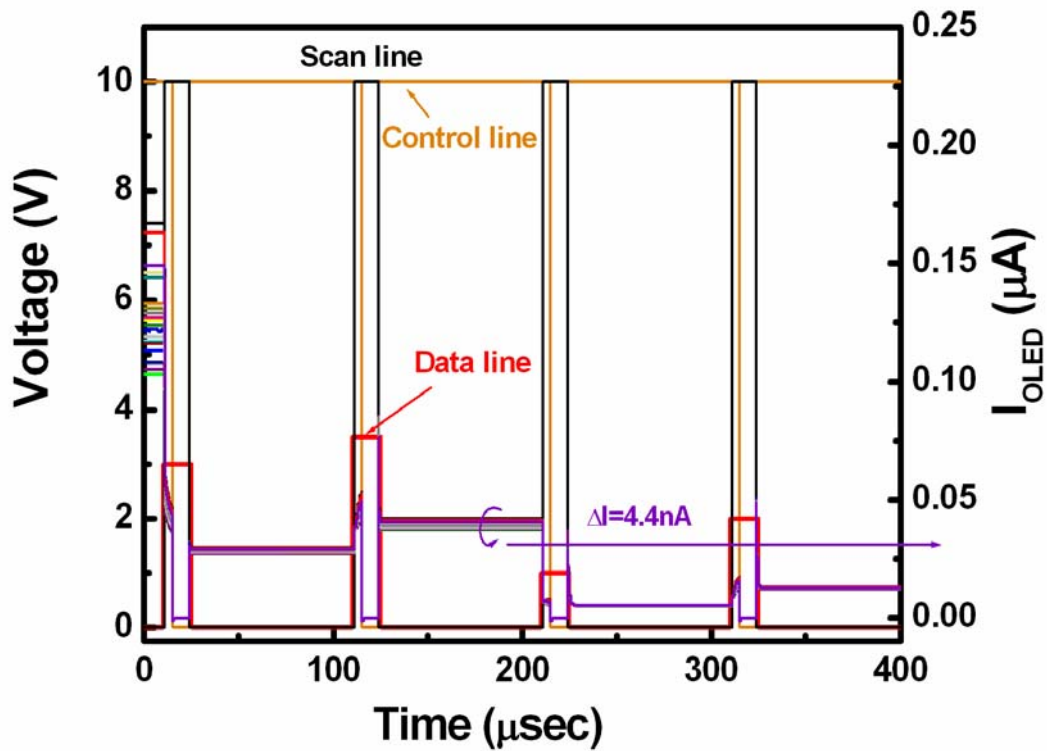


Fig. 3-38. Variations of the proposed circuit simulation with data voltage = 3, 3.5, 1, 2V.

However, the variations suddenly rose when low data voltage is followed by high input data voltage immediately. As shown in Fig. 3-39, the data voltage changes from 0.5V to 5V showing the largest variation about 42% that is serious problem in the proposed pixel circuit. It is ascribed to large data voltage stored in the capacitor is hard to achieve in limited timing period. Two methods are exercised to eliminate this phenomenon in the following discussions.

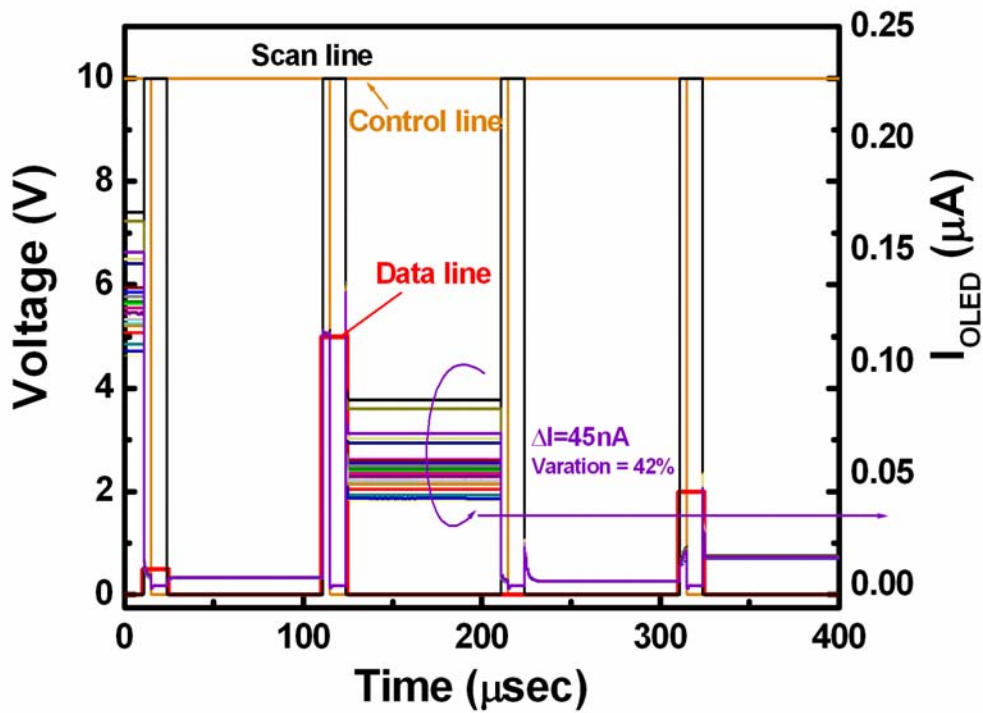


Fig. 3-39. Variations of proposed circuit simulation with data voltage = 0.5, 5, 0, 2V.

First, the reset period  $T_1$  and data period  $T_2$  are prolonged to  $20 \mu\text{sec}$  and  $14 \mu\text{sec}$  from initial condition (Table 3-1) to enhance the data voltage stored in the capacitor. Parameters of proposed circuit simulation with changed timing period are arranged in Table 3-2.

Devices	TFT1、TFT3、 TFT4、TFT5	TFT2	Cs
	$6 \mu\text{m}/6 \mu\text{m}$	$80 \mu\text{m}/6 \mu\text{m}$	1pF
Signals	Vdd	Vctrl, Vsel	
	10V	0V~10V	
Timing Period	Reset Period T1	Data Period T2	Emission Period T3
	$20 \mu\text{sec}$	$14 \mu\text{sec}$	$76 \mu\text{sec}$

Table 3-2. Parameters of proposed circuit simulation with changed timing period.

The simulation results are shown in Fig. 3-40 and the variations of OLED current are reduced to 21.2nA corresponding 11% effectively.

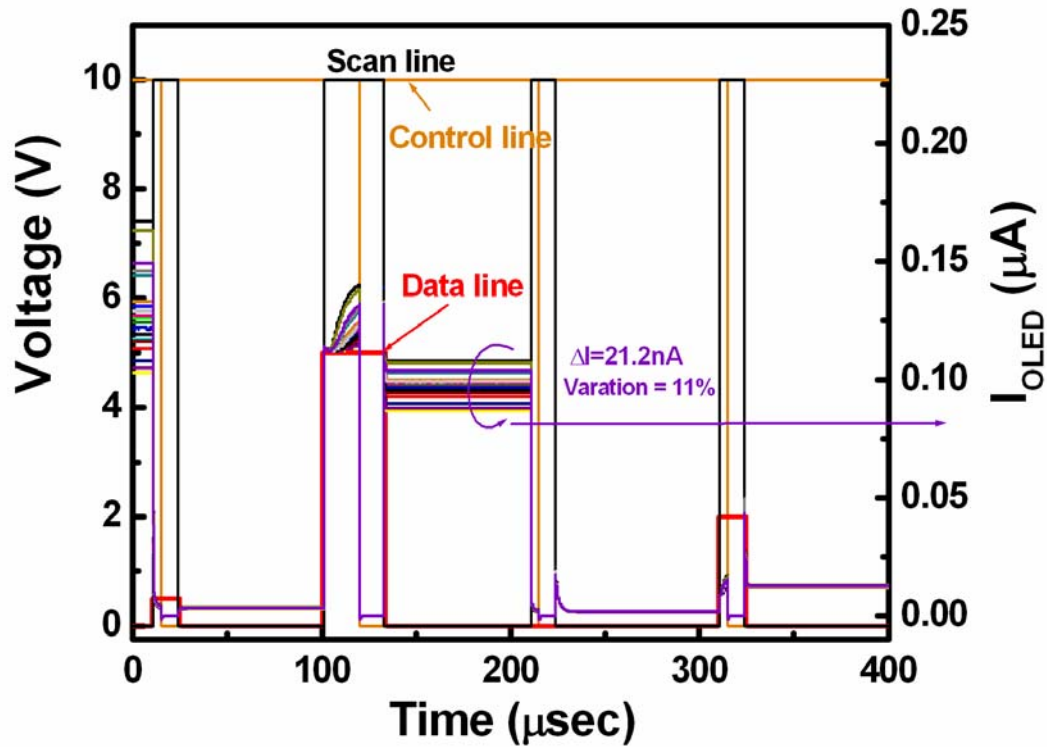


Fig. 3-40. Variations of proposed circuit simulation with changed timing period.

Second, the size of TFT3 and TFT4 can be enlarged, for example, the W/L ratio is enlarged to  $24 \mu\text{m}/6 \mu\text{m}$  for examining output current variations. It is obvious that current variations of proposed circuit simulation with changed device dimension reduced to 33.9nA corresponding 17% effectively shown in Fig. 3-41. Parameters of proposed circuit simulation with changed device dimension are arranged in Table 3-3.

Devices	TFT1、TFT5	TFT3、TFT4	TFT2	Cs
	6 $\mu\text{m}/6 \mu\text{m}$	24 $\mu\text{m}/6 \mu\text{m}$	80 $\mu\text{m}/6 \mu\text{m}$	1pF
Signals	Vdd		Vctrl, Vsel	
	10V		0V~10V	
Timing Period	Reset Period T1	Data Period T2	Emission Period T3	
	5 $\mu\text{sec}$	10 $\mu\text{sec}$	85 $\mu\text{sec}$	

Table 3-3. Parameters of the proposed circuit simulation with changed device dimension.

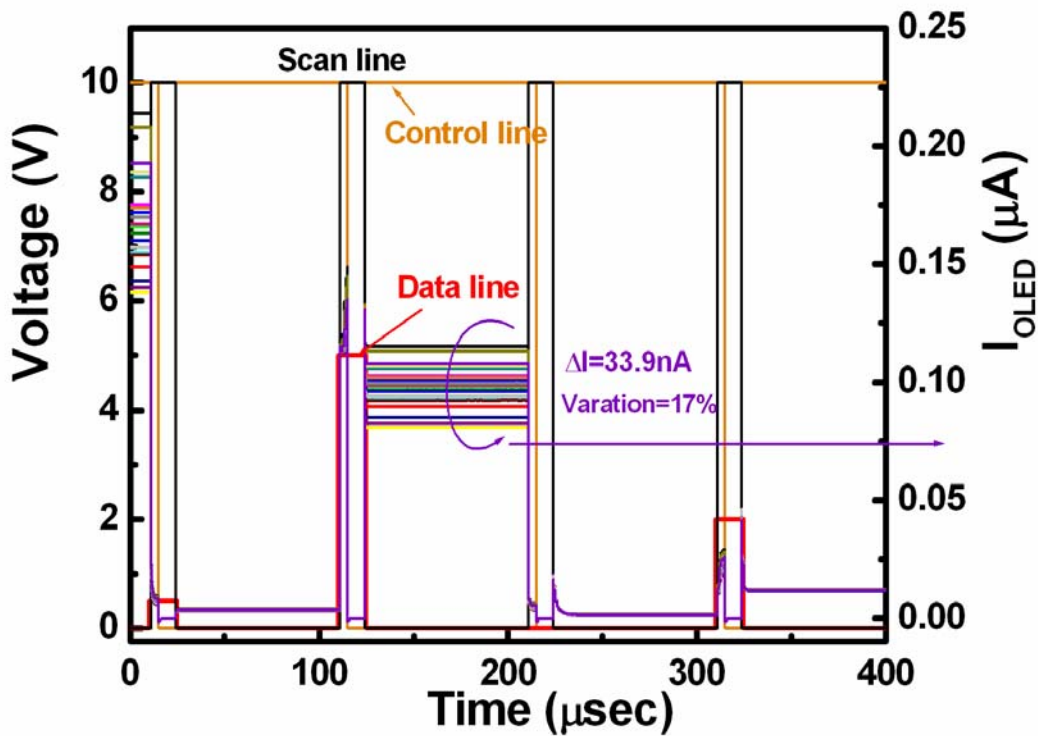


Fig. 3-41. Variations of the proposed circuit simulation with changed device dimension.

Both the charging time and device dimension can reduce the current variation effectively; therefore, two approaches are combined to obtain excellent results. Parameters of the proposed circuit simulation with changed timing period and device

dimension are listed in Table 3-4. The simulated results of current variations in proposed circuit with changed timing period and device dimension are shown in Fig. 3-42. The worst case of output current deviation of modified pixel circuit is reduced to around 10nA corresponding 5% variation.

Devices	TFT1、TFT5	TFT3、TFT4	TFT2	Cs
	6 $\mu\text{m}/6 \mu\text{m}$	24 $\mu\text{m}/6 \mu\text{m}$	80 $\mu\text{m}/6 \mu\text{m}$	1pF
Signals	Vdd		Vctrl, Vsel	
	10V		0V~10V	
Timing Period	Reset Period T1	Data Period T2	Emission Period T3	
	20 $\mu\text{sec}$	14 $\mu\text{sec}$	76 $\mu\text{sec}$	

Table 4-4. Parameters of proposed circuit simulation with changed timing period and device dimension.

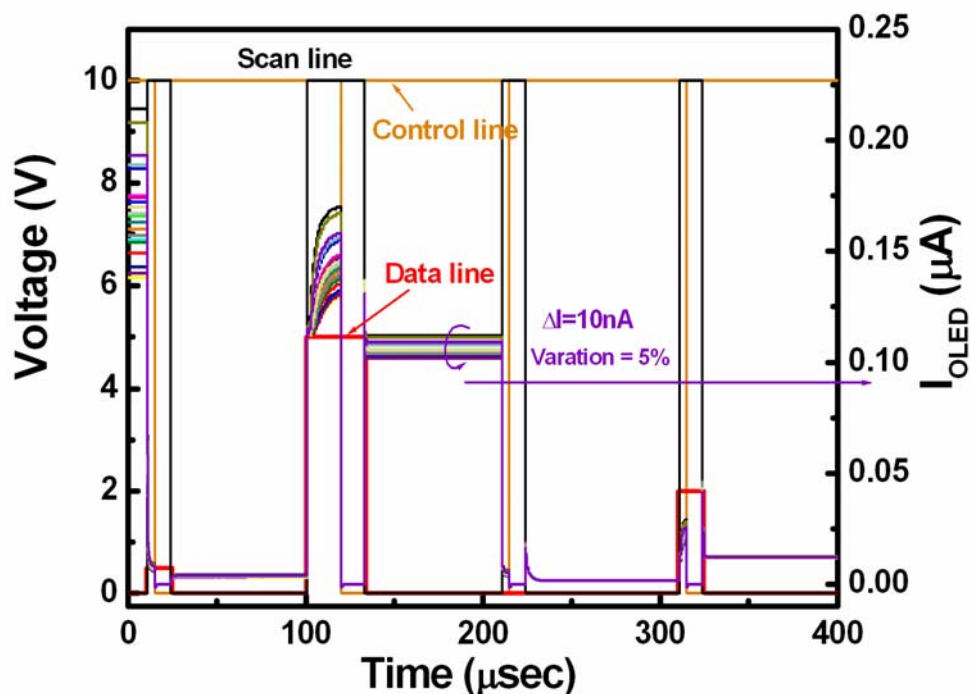


Fig. 3-42. Variations of proposed circuit simulation with changed timing period and device dimension.

### 3.9 Summary

In this chapter, dimensional effects of transistors and storage capacitor in conventional pixel circuit are simulated proving individual functions. Besides, to get better image quality, all kinds of pixel driving circuits for AMOLED are introduced and classified in detail according to the compensation principles and techniques. These compensation pixel circuits are so necessary due to the electrical characteristic variations resulted from the fluctuated laser energy density and each kind of design has its own superiorities and inferiorities.

Compared these pixel circuits, digital driving method needs high addressing speed or small pixel pitch causing higher power consumption or complex processes for high resolution and high gray scale display. Since high addressing speed is difficult for time ratio method, and the decrease of a pixel pitch may be hard to achieve for area ratio method.

On the other hand, current programming method compensates both threshold voltage and mobility variation, but it maybe a critical problem that takes long charging time when low data current occurs in current copy method. Otherwise, if current mirror method is adopted having matching transistor issues.

Though voltage programming methods can only compensate the threshold voltage variation, they are more attractive to integrate poly-Si TFT data drivers on the display panel. It is believed that the voltage programming method is more beneficial than any other compensation methods when realizing better uniformity and system on panel. Two new voltage modulated low-temperature polycrystalline silicon thin-film transistors pixel circuits for active matrix organic light emitting diodes are also

proposed and verified.

The first pixel circuit shows high immunity to the threshold voltage variation of poly-Si TFT characteristics, which can produce uniform display image for AMOLED. From the transient simulation results and Monte Carlo simulation results, proposed pixel circuit shows threshold voltage compensation function. The non-uniformity of the proposed pixel circuit can be reduced below 10%.

To eliminate the current flow through OLED during the reset period, a p-channel TFT is replaced to block the emission current through OLED. Compared with conventional 2T1C pixel circuit and other pixel, the new pixel circuits show much consistence of driving current against threshold voltage variation.

Approaching real condition of proposed pixel circuit applied to products is investigated and operated in several frames. The variations suddenly rose when low data voltage is followed by high input data voltage. It is ascribed to large data voltage stored in the capacitor is hard to achieve in limited timing period. Both the charging time and device dimension can reduce the current variation effects; two approaches are combined to obtain excellent results. The worst case assumption of the output current difference of modified pixel circuit is around 10nA corresponding 5% variation.