A New Pixel Circuit for Driving Organic Light-Emitting Diode With Low Temperature Polycrystalline Silicon Thin-Film Transistors

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***Abstract*—A new pixel circuit design for active matrix organic light-emitting diode (AMOLED), based on the low-temperature polycrystalline silicon thin-film transistors (LTPS-TFTs) is proposed and verified by SPICE simulation. Threshold voltage compensation pixel circuit consisting of four n-type TFTs, one p-type TFT, one additional control signal, and one storage capacitor is used to enhance display image quality. The simulation results show that this pixel circuit has high immunity to the variation of poly-Si TFT characteristics.**

***Index Terms*—Active matrix organic light-emitting diode (AMOLED), low-temperature polycrystalline silicon thin-film transistors (LTPS-TFTs), pixel design, SPICE simulation.**

I. INTRODUCTION

ORGANIC light-emitting diode (OLED) displays are widely researched and developed nowadays due to various advantages such as wide viewing angle, fast response time, compact, simple structure, and light weight [1]–[14]. Although the design of passive matrix OLED is simple compared with active matrix OLED, it can only be used for low-level products, because when applied in the high resolution displays, it demands high voltage to achieve the required average brightness. This will lead to higher power consumption in each row/column line and the higher instantaneous luminance will degrade OLED device. Therefore, active matrix driving methods are better for displays with high resolution and large panel size [1]. In this paper, low temperature poly-Si thin-film transistors (LTPS-TFTs) are used to drive OLED device, since they have possession of higher current capability due to the higher mobility than that of amorphous Si TFTs.

Though LTPS-TFTs have good characteristics, the inevitable nonuniformity problem is encountered because of process variation such as uncontrollable gate oxide trap density and grain size of poly-Si. As a result, various compensation methods have been reported which can be classified into voltage driving [1]–[8], [12], current driving [6], [9], digital driving [13] and other novel methods [10], [14]. Although the current programming methods can compensate both threshold voltage and mobility variation, they need very high addressing speed for high resolution displays. Although the voltage programming methods can only compensate the variation of threshold voltage and can employ data drivers which can be integrated in the panel.

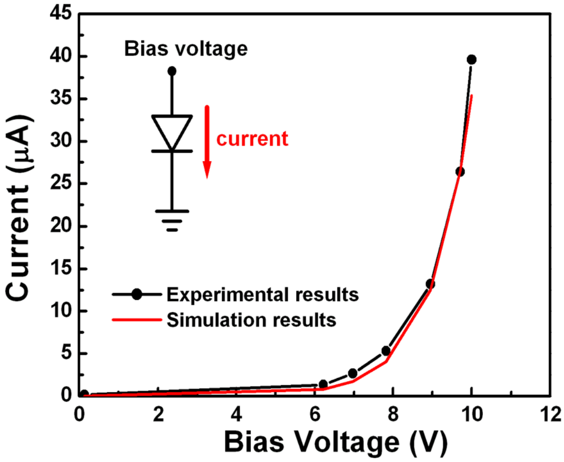

Fig. 1. Measured and simulated OLED current versus bias voltage characteristics. (Color version available online at http://ieeexplore.ieee.org.)

In this paper, a new voltage programming pixel circuit which consists of four n-type TFTs, one p-type TFT, a storage capacitor, and one additional control signal is developed. The simulation results show that pixel design is capable of reducing the nonuniformity of brightness problem of conventional pixel circuit.

II. CONVENTIONAL PIXEL CIRCUIT FOR AMOLEDS

In the beginning, our pixel design started from the measured and simulated OLED current versus bias voltage characteristics, which is shown in Fig. 1. The model parameters were extracted by BSIMPro v2. Attributing to OLEDs are current driving devices, gray scale of the display can be achieved by modulating the current level pixel to pixel. In this work, the OLED area is supposed to be 60 (μm) $*$ 220 (μm), corresponding to a 4-in QVGA specification.

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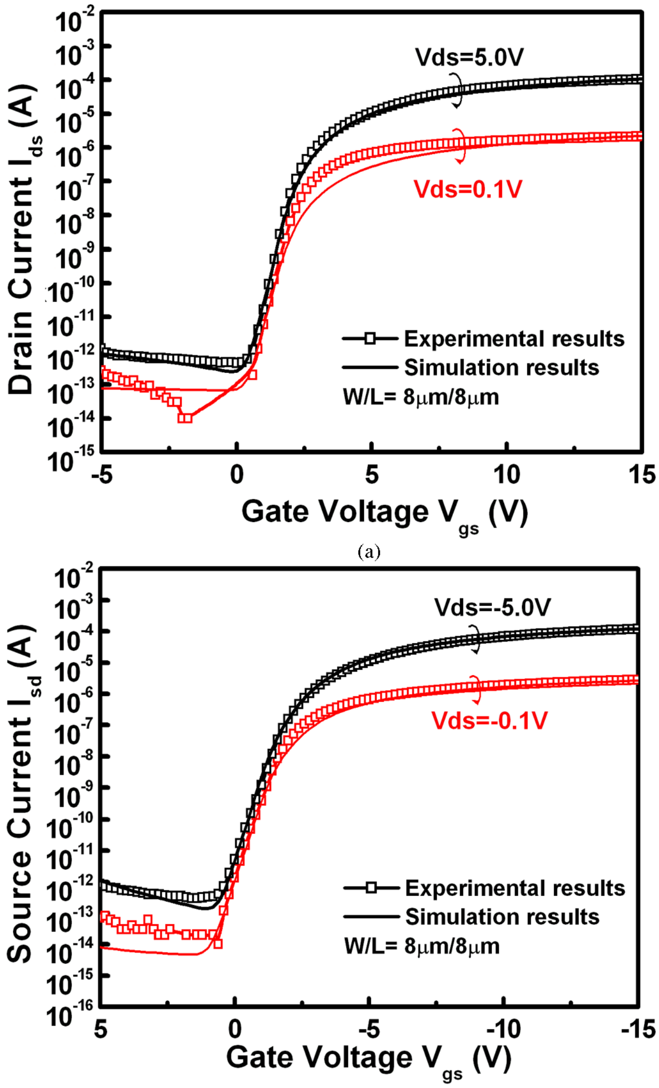


(a)

(b)

Fig. 2. Measured and simulated transfer characteristics of: (a) n-channel TFTs and (b) p-channel TFTs.

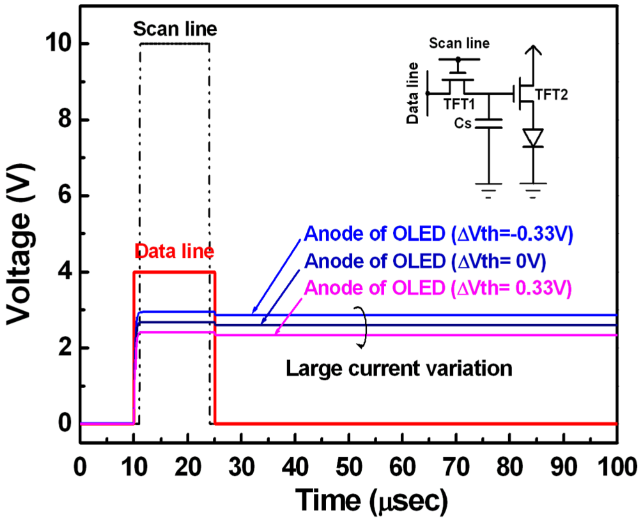


Fig. 3. Schematic of the typical n-type TFT pixel circuit and simulation results.

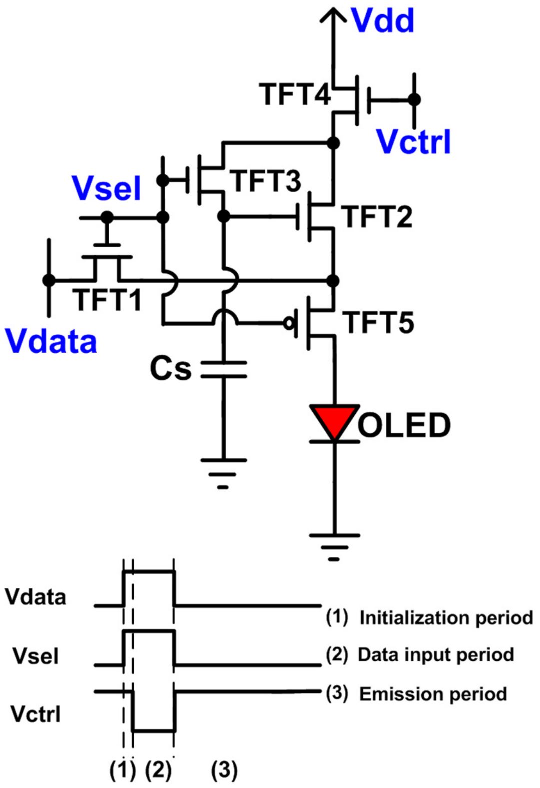


Fig. 4. Proposed circuit schematic and driving signals of voltage compensation circuit for AMOLED.

We measured the electrical characteristics of the LTPS TFTs for SPICE modeling. Electrical characteristics were measured from HP4156C measurement system and model parameters also extracted by BSIMPro v2. The model used in simulation was RPI poly-Si TFT model (LEVEL 62). Fig. 2(a) and (b) shows the measured and simulated transfer characteristic of n-channel and p-channel LTPS TFTs which show good fitting results.

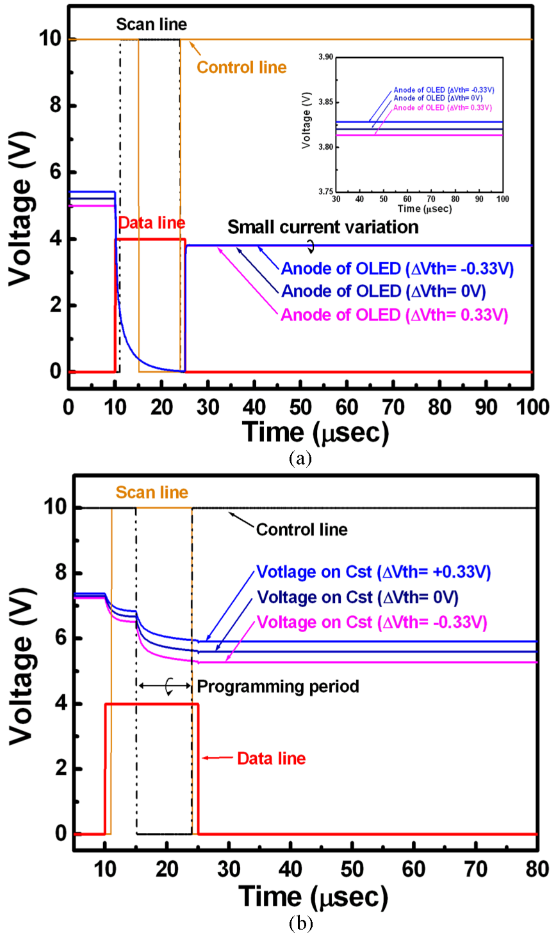
Fig. 3 shows the typical schematic of n-type LTPS TFT pixel circuit and its simulation results. In this case, the threshold voltage deviation of driving TFTs is assumed at 0.33 V. It is observed that the anode of OLED is dependent on the threshold voltage deviation which is a key factor in brightness. If the driving transistor is biased in the saturation region, the drain current will be determined only by gate-source voltage of driving transistor TFT2 and becomes

$$I_{\mathrm{OLED}} = \frac{1}{2}k_2(V_{gs\_T2} - V_{th\_T2})^2 \left(k_2 = \mu Cox\frac{W_2}{L_2}\right) \quad (1)$$

Due to the spatial variation of threshold voltage in the driving transistor TFT2 caused by process variation, nonuniform image quality over the display will become a critical issue.

III. VOLTAGE COMPENSATION PIXEL CIRCUIT FOR AMOLEDs

Fig. 4 shows the proposed pixel structure modifying we reported before [3] and the signal driving scheme, respectively. It has five TFTs and a capacitor. TFT1, TFT3, TFT4, and TFT5 are switching TFTs and TFT2 is a driving TFT. The operation scheme and compensation principle are described as follows.



(a)

(b)

Fig. 5. An example of adriving scheme for: (a) the proposed pixel circuit at $\mathrm{Vdata} = 4$ V and (b) the stored data voltage in the capacitor with varied threshold voltages of TFTs. (Color version available online at http://ieeexplore.ieee.org.)

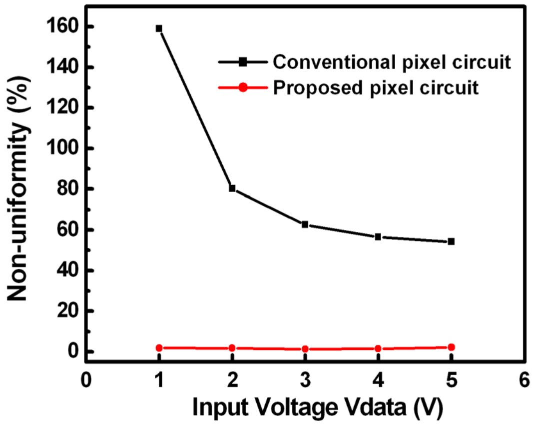


Fig. 6. Nonuniformity of the output current due to threshold voltage variation in the device performance. (Color version available online at http://ieeexplore.ieee.org.)

1) *Initialization Period*: In 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.

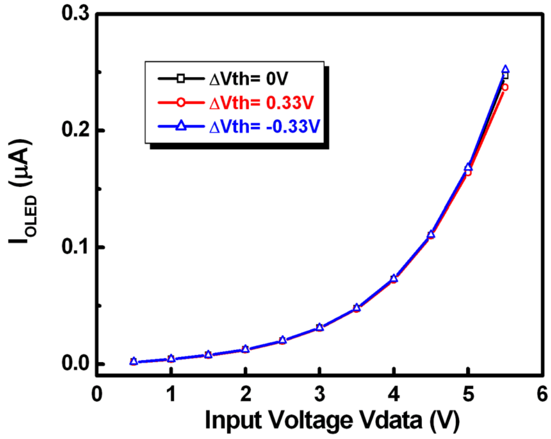


Fig. 7. Simulation results showing the range of current flowing through the OLED at different Vdata and threshold voltage variation ($\Delta\mathrm{Vth} = -0.33$ V, 0 V, and $+0.33$ V). (Color version available online at http://ieeexplore.ieee.org.)

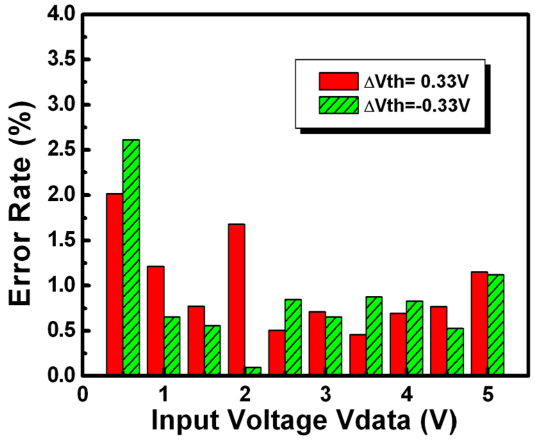


Fig. 8. Error rate of output current in our proposed pixel circuit due to the threshold voltage variation. It is clear that the output current error rate is below 3% in our proposed pixel circuit when input data voltage ranges 0.5–5 V. (Color version available online at http://ieeexplore.ieee.org.)

2) *Data Input Period*: Switching transistors TFT1 and TFT3, and driving transistor TFT2 are active and TFT4 and TFT5 are turned off. $\mathrm{Vdata} + \mathrm{V_{th\_T2}}$ stored in Cs during the second period, because TFT2 is diode connection.

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

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

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 new pixel circuit shows much consistence of driving current against threshold voltage variation in Fig. 5(a). It is demonstrated that the anodes of OLED devices are insensitive to different threshold voltages. Fig. 5(b) 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. 6 shows the nonuniformity in output current of an OLED simulated with combined Vth variation ($\Delta\mathrm{Vth} = -0.33$ V, 0 V, and $+0.33$ V) of poly-Si TFT during programming. The nonuniformity 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 nonuniformity in output current of an OLED effectively.

Fig. 7 shows the transfer characteristics of the pixel circuit at different $\mathrm{Vdata}$and threshold voltage variation ($\Delta\mathrm{Vth} = -0.33$ V, 0 V, and $+0.33$ V). It shows that output current of OLED is nearly independent of threshold voltage deviation with different input data signal. Our simulation results are plotted in Fig. 8. The output current errors of conventional pixel circuit are all above 20% when input data voltage ranges 0.5–5 V, which is below 3% in our proposed pixel circuit.

IV. CONCLUSIONS

A new voltage modulated low-temperature polycrystalline silicon LTPS-TFTs pixel circuit for AMOLEDs is proposed. The pixel circuit is formed by four n-type TFTs, one p-type TFT, one additional control signal, and a storage capacitor. The proposed pixel design employs diode-connected concept. The circuit shows high immunity to the threshold voltage variation of poly-Si TFT characteristics which will lead to uniform display image for AMOLED.

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REFERENCES

[1] M. Kimura, I. Yudasaka, S. Kanbe, H. Kobayashi, H. Kiguchi, S. I. Seki, S. Miyashita, T. Shimoda, T. Ozawa, K. Kitawada, T. Nakazawa, W. Miyazawa, and H. Ohshima, "Low-temperature polysilicon thin-film transistor driving with integrated driver for high-resolution light emitting polymer display," *IEEE Trans. Electron Devices*, vol. 46, no. 12, pp. 2282–2288, Dec. 1999.

[2] C. W. Lin, D. Z. Peng, R. Lee, Y. F. Shih, C. K. Jan, M. H. Hsieh, S. C. Chang, and Y. M. Tsai, "Advanced poly-Si device and circuitry for AMOLED and high-integration AMLCD," in *Int. Display Manufacturing Conf.*, 2005, pp. 315–318.

[3] B. T. Chen, Y. J. Kuo, C. C. Pai, C. C. Tsai, H. C. Cheng, and Y. H. Tai, "A new pixel circuit for driving organic light emitting diodes with low temperature polycrystalline thin film transistors," in *Int. Display Manufacturing Conf.erence*, 2005, pp. 378–381.

[4] J. H. Kim and J. Kanicki, "200 dpi 3-a-Si:H TFT's voltage-driven AM-PLED's," in *SID Tech. Dig.*, 2003, pp. 18–21.

[5] J. H. Lee, B. H. You, W. J. Nam, H. J. Lee, and M. K. Han, "A new a-Si:H TFT pixel design compensating threshold voltage degradation of TFT and OLED," in *SID Tech. Dig.*, 2004, pp. 264–267.

[6] R. M. A. Dawson, Z. Shen, D. A. Furst, S. Connor, J. Hsu, M. G. Kane, R. G. Stewart, A. Ipri, C. N. King, P. J. Green, R. T. Flegal, S. Pearson, W. A. Barrow, E. Dickey, K. Ping, S. Robinson, C. W. Tang, S. Van Slyke, F. Chen, J. Shi, M. H. Lu, and J. C. Sturm, "The impact of the transient response of organic light emitting diodes on the design of active matrix OLED displays," in *IEDM Tech. Dig.*, 1998, pp. 875–878.

[7] S. M. Choi, O. K. Kwon, and H. K. Chung, "An improved voltage programmed pixel structure for large size and high resolution AM-OLED displays," in *SID Tech. Dig.*, 2004, pp. 260–263.

[8] J. C. Goh, H. J. Chung, and J. Jang, "A new pixel circuit for active matrix organic light emitting diodes," *IEEE Electron Device Lett.*, vol. 23, no. 9, pp. 544–546, Sep. 2002.

[9] Y. He, R. Hattori, and J. Kanicki, "Four-thin film transistor pixel electrode circuits for active-matrix organic light-emitting displays," *Jpn. J. Appl. Phys.*, vol. 40, pp. 1199–1208, 2001.

[10] Y. C. Lin and H. P. D. Shsieh, "Improvement of brightness uniformity by AC driving scheme for AMOLED display," *IEEE Electron Device Lett.*, vol. 25, no. 11, pp. 728–730, Nov. 2004.

[11] J. J. Lih, C. F. Sung, C. H. Li, T. H. Hsiao, and H. H. Lee, "Comparison of a-Si and poly-Si for AMOLEDs," in *SID Tech. Dig.*, 2004, pp. 1504–1507.

[12] S. W. B. Tam and T. Shimoda, "Modeling and design of polysilicon drive circuits for OLED displays," in *SID Tech. Dig.*, 2004, pp. 1406–1409.

[13] M. Mizukami, K. Inukai, H. Yamagata, T. Konuma, T. Nishi, J. Koyama, S. Yamazaki, and T. Tsutsui, "6-bit digital VGA OLED," in *SID Tech. Dig.*, 2000, pp. 912–915.

[14] H. Akimoto, H. Kageyama, Y. Shimizu, H. Awakura, S. Nishitani, and T. Sato, "An innovative pixel-driving scheme for 64-level gray-scale full-color active matrix OLED displays," in *SID Tech. Dig.*, 2002, pp. 972–975.

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