An a-InGaZnO TFT Pixel Circuit Compensating Threshold Voltage and Mobility Variations in AMOLEDs

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***Abstract*—In this paper, we proposed a novel voltage-programmed pixel circuit based on amorphous indium gallium zinc-oxide thin-film transistor (a-InGaZnO TFT) for active-matrix organic light-emitting display (AMOLED) with an enhanced electrical stability and uniformity. Through an extensive simulation work based on a-InGaZnO TFT and OLED experimental data, we confirm that the proposed pixel circuit can compensate for both mobility variation and threshold voltage shift of the driving TFT.**

***Index Terms*—Active-matrix organic light-emitting display (AMOLED), amorphous indium gallium zinc oxide (a-InGaZnO), mobility variation, pixel circuit, thin-film transistor (TFT).**

I. Introduction

RECENTLY actives-matrix organic light-emitting display (AMOLED) has been a focus among display industries due to its superior properties such as fast response time, low power consumption, and wide-viewing angle over liquid crystal displays (LCDs) [1]–[3]. So far as a backplane technology for AMOLEDs, two types of matured thin-film transistor (TFT) technologies are considered to be applied in the pixel circuit; hydrogenated amorphous silicon (a-Si:H) TFT and low-temperature polycrystalline silicon (LTPS) TFT. However, since the OLED current degrades over time due to the threshold voltage shift of a-Si:H TFT by the operation bias [4], or since the OLED current is not uniform due to the localized crystallization on the panel during the LTPS TFT fabrication [5], the simple pixel circuit with two TFT and on capacitor (2T1C) cannot be used for AMOLEDs, which requires the development of novel TFT technologies based on other semiconductor materials as alternative approaches [6]–[8]. Among all, amorphous indium gallium zinc oxide (a-InGaZnO) TFT possess certain advantages including visible transparency, low processing temperature, good uniformity, decent mobility, low off-current, sharp sub-threshold swing, and potentially better electrical stability, which make it very favorable for AMOLEDs [8]–[10]. Although a-InGaZnO TFT offers prominent device performance, its threshold voltage instability under gate voltage bias-stress and mobility non-uniformityduring the TFT fabrication over large area still remains as problems to be used for AMOLEDs.

To resolve these problems, several voltage-programmed pixel circuits based on a-InGaZnO TFT have been reported [11]–[14]. Mo *et al.* proposed a five-TFT and two-capacitor pixel circuit to compensate the positive and negative threshold voltage and OLED degradation [11]. Jung *et al.* alsodeveloped a five-TFT and one-capacitor voltage-programmed pixel circuit which can compensate for threshold voltage degradation of a-InGaZnO TFT [15]. However, none of AMOLED pixel circuits developed so far has been reported to compensate the inherent mobility variations of TFT over large size panel, which results in the non-uniformity on the image of AMOLEDs.

This paper presents a novel a-InGaZnO TFT based voltage-programmed pixel circuit for AMOLEDs, which can compensate the mobility variation as well as both positive and negative threshold voltage variations of driving TFT. The function of mobility variation compensate for this pixel circuit is experimentally verified.

II. TFT Fabrication and Characterization

In order to extract the electrical parameters of TFT to be used for the pixel circuit, a-In-GaZnO TFTs were fabricated on glass substrates. The gate electrode Ti (5 nm)/Au (40 nm)/Ti (5 nm) was deposited by electron-beam and patterned by lift off. The gate insulator $SiO_2(=\ 200$ nm) and a-InGaZnO(= 20 nm) thin films were both deposited by RF magnetron sputtering at room temperature, and a-InGaZnO layer was patterned by wet etching. It should be noted that the thickness of a-IGZO layer is set as 20 nm in order to maintain the threshold voltage no more than 1 V as well as achieving the optimum properties of a-IGZO TFT. The source/drain electrodes Ti (5 nm)/Au (100 nm)/Ti (5 nm) were deposited by electron-beam and patterned by lift off [16]. The measured TFT transfer characteristics and the cross-sectional schematic of fabricated TFT are shown in Fig. 1. Then a-InGaZnO TFT SPICE model was developed based on the Rensselaer Polytechnic Institute (RPI) a-Si:H TFT model. SPICE parameters needed for circuit simulations are extracted from the measurement data, and used to simulate the TFT transfer characteristics (illustrated as the open circles in

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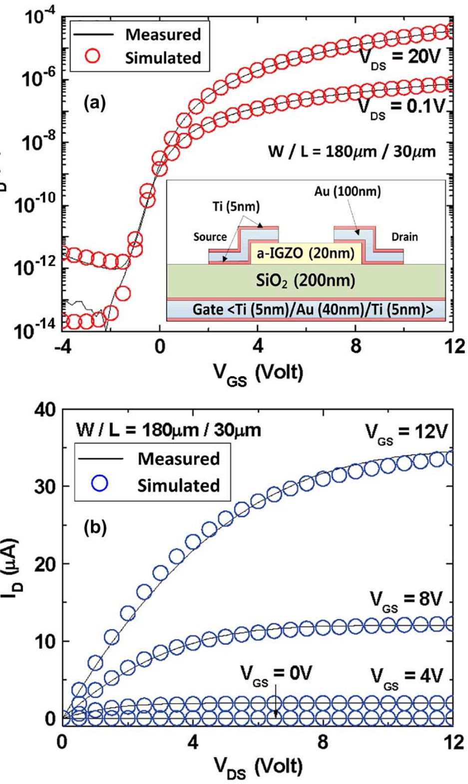

Fig. 1. Measured and simulated (by HSPICE) a-InGaZnO TFT. (a) transfer characteristics. (b) Output curves.

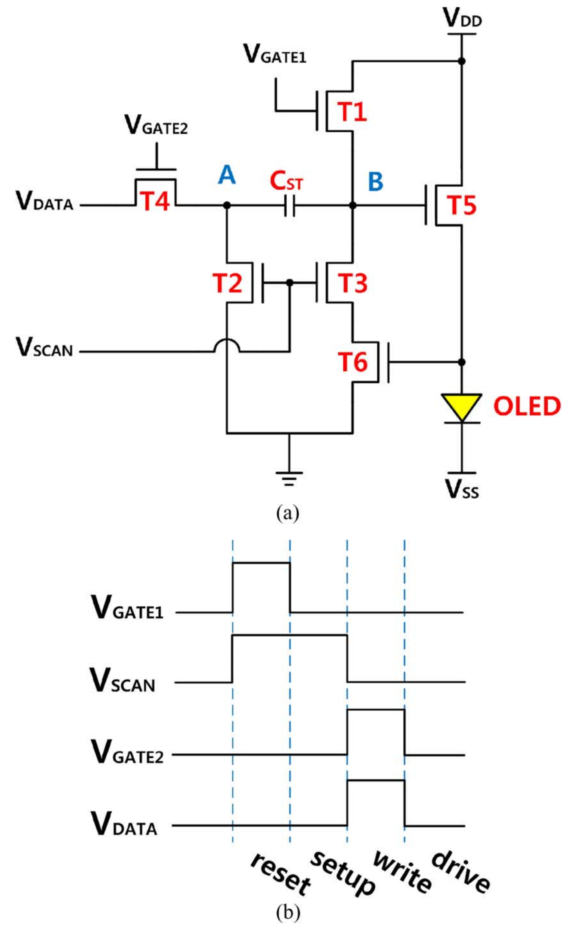

Fig. 2. (a) Schematic circuit diagram and (b) operational waveforms of the proposed voltage-programmed pixel circuit.

Fig. 1). To verify the proposed pixel circuit, simulations were performed using H-SPICE software supported by IC design education center (IDEC). The OLED model used in the simulation consists of two junction diodes and two series resistors connected in parallel with a capacitor [17].

III. Proposed Circuit Configuration and Its Operation

As shown in Fig. 2(a), the proposed AMOLED pixel circuit is composed of one driving TFT (T5), one set-up TFT (T6), four switching TFTs (T1, T2, T3, and T4), one capacitor. Fig. 2(b) show the driving schematics of this proposed pixel circuit. V_{SCAN}, V_{GATE1}, and V_{GATE2} are for control signal lines while V_{DATA}, V_{DD}, and V_{SS} refer to a data voltage signal, a constant voltage source line, and a ground line, respectively. The operation of the proposed circuit is divided in four periods; reset, setup, write, and drive. The detailed operation scheme and compensation principle of the proposed voltage-programmed pixel circuit are described as follows.

A. Reset Period

During the reset period, the control signal V_{GATE1} and V_{SCAN} are set to high level, turning on the T1, T2, and T3, while V_{GATE2} and V_{DATA} are set to low level. By turning on T1, T5 operates as the diode with its gate and drain node connected, of which turn-on voltage equals to the threshold voltage of T1. Because the drain voltage of T5 is set as V_{DD}, the gate node of the driving TFT (T5) is reset to a voltage equal to the V_{DD} minus the T1's threshold voltage. In this period, since T5 is maintained to be turned on, the current flows from V_{DD} to OLED and emit the light.

B. Setup Period

During the set-up period, the previous scan line (V_{GATE1}) is set to low level, whereas the other signal line (V_{SCAN}) maintain sits previous voltage level (high). Since the V_{SCAN} keeps turning on T2 and T3, the gate node of driving TFT (T5) is starts to be discharged until it reaches to the compensation voltage for the threshold voltage of T5 as well as that of T6. Moreover, in this period, the compensation for the mobility variation of driving TFT (T5) also occurs at the same time. If the mobility of T5 gets lower, the resistance of T5 becomes increased, resulting in the source node voltage of T5 decreases by ΔV_{μ_T5} since the OLED has a fixed resistance. As a result, the gate node voltage of T5 increases by ΔV_{μ_T5}, which approximately depends on the mobility of T5. Thus, the mobility variations of T5 can be controlled by controlling ΔV_{μ_T5}in this period. Therefore, the final gate node voltage of T5 during this period equals to $V_{comp} = V_{TH\_T5} + V_{TH\_T6} + \Delta V_{\mu\_T5}$.

C. Write Period

During this period, (V_{GATE1}) is maintained as low level and V_{SCAN} turns to low level while (V_{GATE2}) is set to high level in order to write data signal. A data voltage goes through T4,

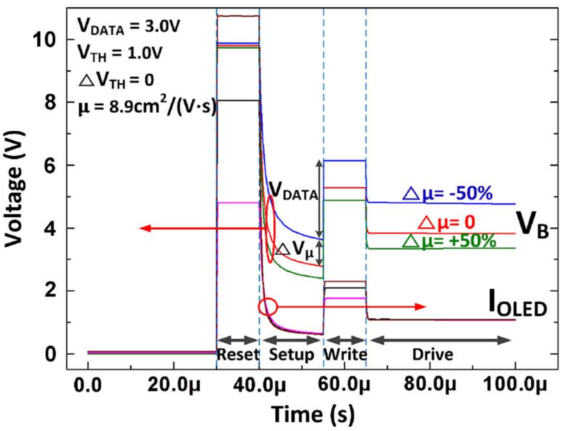

Fig. 3. Simulated responses of the node voltage and OLED current for the proposed pixel circuit in time domain.

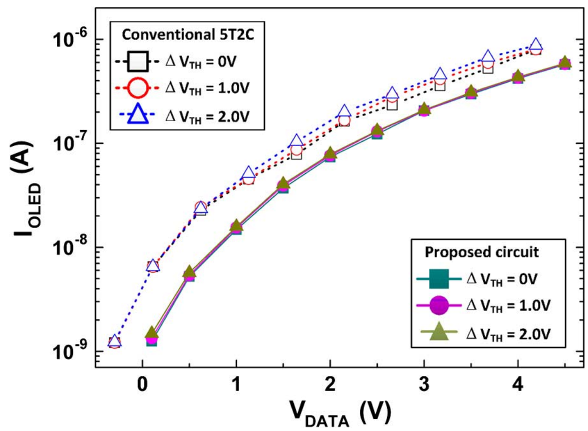

Fig. 4. I_{OLED} as a function of V_{DATA} of the proposed (closed symbols) and conventional 5T2C (open circuit) pixel circuit.

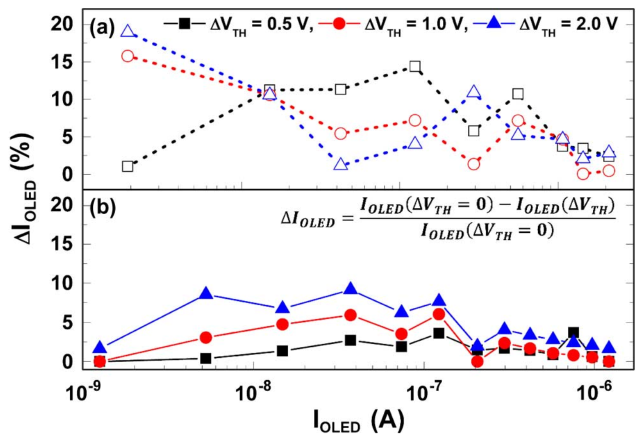

Fig. 5. ΔI_{OLED} as a function of I_{OLED} for different levels of positive ΔV_{TH} shift in (a) conventional 5T2C and (b) proposed pixel circuits.

andat the same time this data voltage is bootstrapped to the gate node (B) of the driving TFT (T5) by the C_{ST}. Therefore, the gate node voltage of the driving TFT (T5) is changed to the bootstrapped data voltage plus the compensation voltage stored in the previous period $(V_{DATA} + V_{comp})$.

D. Drive Period

At last, during the drive period, all signal lines are set to low level and the driving TFT operates in the saturation regime to drive the programmed OLED current. The voltage stored in the storage capacitor (C_{ST}) during the write period will compensate the OLED current both for threshold voltage and mobility variations of driving TFT (T5). Note that the OLED current is equal to the corresponding drain current of T5, as in the equation

$$\begin{aligned} I_{\rm OLED} &= \frac{k}{2}(V_{\rm GS} - V_{\rm TH})^2 \\ V_{\rm GS} &= V_{\rm DATA} + V_{\rm COMP} \\ I_{\rm OLED} &= \frac{k}{2}(V_{\rm DATA} + V_{\rm TH\_T5} + V_{\rm TH\_T6} \\ &\quad + \Delta V_{\mu\_\rm T5} - V_{TH\_\rm T5})^2 \\ \therefore I_{\rm OLED} &\propto \frac{k}{2}(V_{\rm DATA} + \Delta V_{\mu\_\rm T5})^2 \end{aligned} \tag{1}$$

where $k = \mu C_{ox} W/L$. As shown from (1), the OLED current during the drive period is independent of the mobility and threshold voltage variations of T5 because the mobility variation of T5 is cancelled by the stored voltage ΔV_{μ_T5}. Here we assume that the threshold voltages of T2, T3, and T6 are kept constant during the operation since they act as only switching transistors. Therefore, the threshold voltage and mobility variations of driving TFT (T5) can be compensated effectively, and uniform OLED brightness can be achieved.

Fig. 3 shows the transient simulation results of OLED current and gate node voltage of driving TFT (T5) with a 3.0 V input data for the proposed pixel circuit. It is obviously shown that the mobility variation of the driving TFT (ΔV_{μ}) is detected in the setup period, and added to the gate node of driving TFT (T5), resulting that the OLED current remain unperturbed from the programmed value. It should be noted that if the mobility ofT5 gets higher than other transistors, the negative value of ΔV_{μ} is detected and then subtracted from the programmed data voltage. Therefore the OLED current variation of the proposed pixel circuit can be minimized regardless of any mobility variation.

IV. Simulation Results and Discussion

In order to confirm the performance of the proposed pixel circuit, it is compared with previously reported 5T2C pixel circuit [15]. Fig. 4 shows the OLED currents (I_{OLED}) delivered by previously reported voltage-programmed pixel circuit (5T2C) and by our proposed pixel circuit as a function of V_{DATA}, respectively. Obviously, a wide dynamic I_{OLED} range $(\sim 10^3)$ was achieved by both pixel circuits when the threshold voltage shift is zero $(\Delta V_{TH} = 0\ V)$. However, as shown in Fig. 4, when the drive TFT exhibits 1.0 or 2.0 V of ΔV_{TH}, we can see that OLED current of 5T2C pixel circuit shows small perturbation compared to the proposed circuit. Fig. 5 plots ΔI_{OLED} as a function of I_{OLED} when the threshold voltage shift varies positively from 0.5 to 2.0 V for the previous 5T2C and the proposed pixel circuit. Here the percentage change in $I_{OLED}(\Delta I_{OLED})$ is defined as the ratio of the OLED current difference between OLED currents with varying ΔV_{TH} values to the unperturbed OLED current $(\Delta V_{TH} = 0V)$ for the input data. It is shown that the OLED current variations are significantly reduced as less than 9% even for ΔV_{TH} equals to 2.0 V while the 5T2C pixel circuit shows more than 18% variation.

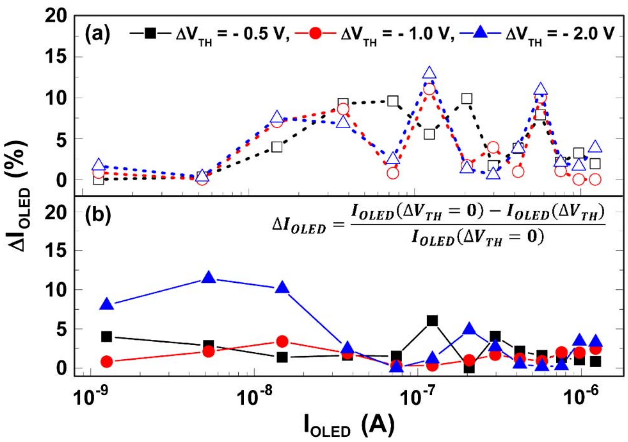

Fig. 6. ΔI_{OLED} as a function of IOLED for different levels of negative ΔV_{TH} shift in (a) conventional 5T2C and (b) proposed pixel circuits.

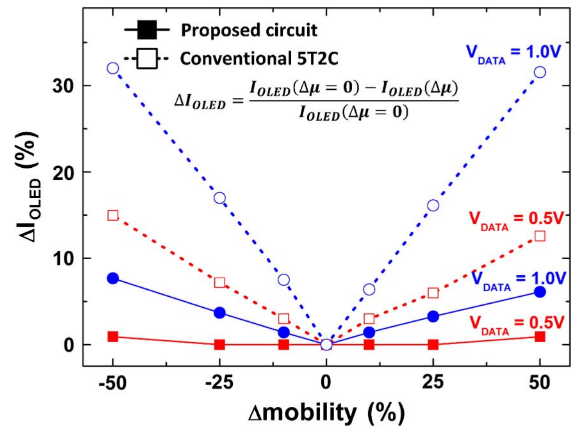

Fig. 7. OLED current error ratio as a function of $\Delta\mathrm{mobility}$ for the proposed and conventional 5T2C pixel circuit.

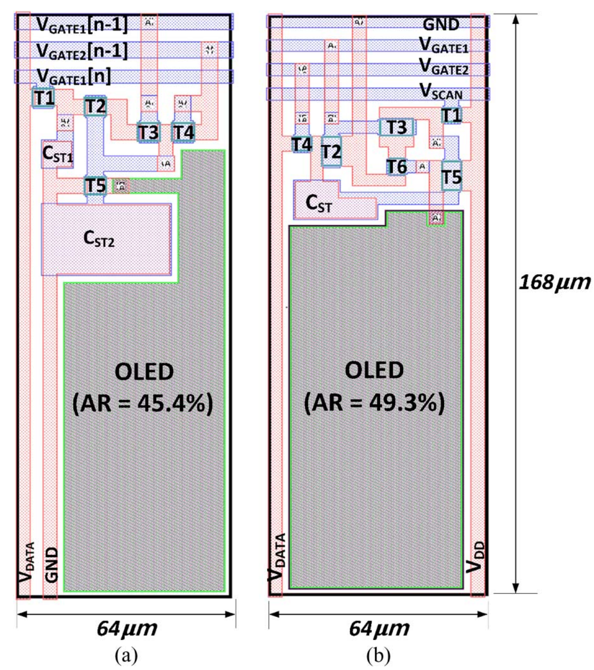

Fig. 8. Schematic layouts of : (a) the conventional pixel with 5-TFTs and 2-capacitors and (b) the proposed pixel with 6-TFTs and 1-capacitor.

On the other hand, since a-IGZO TFT shows n-type semiconductor characteristics, it is required to apply a negative gate voltage in order to turn off the transistor. According to recent reports, it was demonstrated that the threshold voltage of a-IGZO TFT showed a huge negative shift under a negative bias and illumination stress at the same time, which would be an usual stress condition for switch TFTs considering AM-OLED operation environments [18], [19]. Therefore, a high reliability against a negative bias stress is also a critical factor for the a-IGZO pixel electrode circuit in driving an active matrix display. While threshold voltages of driving TFT (T5) remain as the initial values, those of switching TFTs are shifted at this time. Then, we plotted ΔI_{OLED} as a function of I_{OLED} with negative threshold voltage shifts (ΔV_{TH}) varying from -2.0 V to -0.5 V in order to evaluate the effect of the negative (ΔV_{TH}) on the proposed circuit. As shown in Fig. 6, when the V_{TH} of driving TFT is shifted negatively, the proposed voltage-programmed pixel circuit can compensate for negative ΔV_{TH} below 10%, while the 5T2C voltage-programmed pixel circuit still shows over 15% OLED current variation.

Finally, to investigate the mobility compensation ability of the proposed pixel circuit, we assume that the mobility of driving TFT (T5) is swept from -50% to +50% of the initial mobility value, and plot ΔI_{OLED} as a function of $\Delta\mathrm{mobility}$ when $V_{DATA} = 0.5$ and 1.0 V. As shown in the Fig. 7, the maximum error in the OLED current is less than 10% even for ±50% mobility variations while conventional 5T2C pixel circuit has easily over 32% OLED current error for same levels of mobility variation. Therefore, the simulation results indicate that the proposed voltage-programmed pixel circuit has higher immunity to mobility variation of a-InGaZnO TFT from one pixel to another, compared with the conventional 5T2C pixel circuit.

V. Layout of Pixel Circuit

We performed the layout work of the proposed pixel circuit for 9.7 inch in XGA display. The sub-pixel size is set to 64 μm × 168 μm, and considered to be fabricated by 5-mask etch stop process [20]. Here the values of two C_{ST} in the conventional 5T2C pixel circuit are set as 0.02 and 0.7 pF, respectively, while the value of C_{ST} in the proposed pixel circuit is set as 0.2 pF, in order to achieve the best compensation function from each pixel circuit. When compared with the previous 5T2C pixel circuit as shown in Fig. 8, though one extra TFT is inserted in the proposed circuit, the aperture ratio (AR) of the proposed circuit can increase up to 47% by removing one capacitor while the conventional 5T2C pixel circuit has the AR of only 43.6%. Therefore, by improving the aperture ratio, the brightness of the display can be enhanced. Moreover, by removing one capacitor from the conventional 5T2C pixel circuit, the unnecessary dynamic power consumption by the capacitor can be removed, resulting that the proposed pixel circuit is more efficient in the power consumption.

VI. Conclusion

We proposed a novel voltage-programmed pixel circuit based on a-InGaZnO TFT for AMOLEDs. The proposed pixel circuit minimizes the non-uniformity on the display image caused by variations of V_{TH} and mobility. As shown from our simulation results, the non-uniformity of OLED current for the threshold voltage and mobility variation is significantly reduced compared to that of the conventional 5T2C pixel circuit. Through, the proposed a-InGaZnO pixel circuit with a dual-compensating function, we expect a highly stable OLED current can be achieved for a large size, high resolution AMOLEDs.

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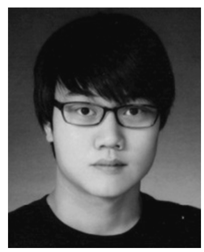

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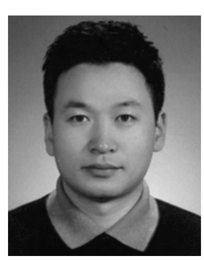

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