# a-IGZO TFT Based Pixel Circuits for AM-OLED Displays

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## Abstract

*In this paper, we analyze application of amorphous Indium–Gallium–Zinc–Oxide thin film transistors (a-InGaZnO TFTs) to voltage-driven pixel electrode circuit that could be used for 4.3-in. wide video graphics array (WVGA) full color active-matrix organic light-emitting displays (AM-OLEDs). Simulation results, based on a-InGaZnO TFT and OLED experimental data, show that both device sizes and operational voltages can be reduced when compared to the same circuit using hydrogenated amorphous silicon (a-Si:H) TFTs. Moreover, the a-InGaZnO TFT pixel circuit can compensate for the threshold voltage variation ($\Delta V_{TH}$) of driving TFT within acceptable operating error range.*

## 1. Introduction

Although hydrogenated amorphous silicon (a-Si:H) thin film transistors (TFT) currently dominate the liquid crystal display (LCD) market due to their uniformity over large area, low cost of fabrication, and mature technology[1], the insufficient field-effect mobility and meta-stable shift in threshold voltage when subject to prolonged gate bias make their application to AM-OLEDs rather difficult. As a result, TFTs based on other semiconductor materials have been explored as an alternative approach [2, 3]. Among all, amorphous In-Ga-Zn-O (a-InGaZnO) TFTs possess certain advantages including visible transparency, low processing temperature, good uniformity, decent mobility, low off-current, sharp subthreshold swing, and potentially better electrical stability, which make them very favorable for AM-OLEDs [3]. So far, most of a-InGaZnO TFT driven AM-OLEDs are reported based on the two or three transistors and one capacitor voltage-programmed pixel circuit. The usage of such circuit requires the a-InGaZnO TFTs to be electrically very stable, which might not be the case [4, 5]. Therefore, whether these circuits are suitable for stable operation AM-OLEDs is still questionable. In this paper, we present a novel a-IGZO TFT based voltage programmed pixel circuits with an enhanced compensation function for device electrical instabilities in comparison to conventional 2-TFT pixel electrode circuits. The proposed circuit provides a wide dynamic OLED current range over lower data voltage levels, which is ideal for a high resolution AM-OLED. We also demonstrate the effect of $\Delta V_{TH}$ on the circuit performance based a-InGaZnO transistors.

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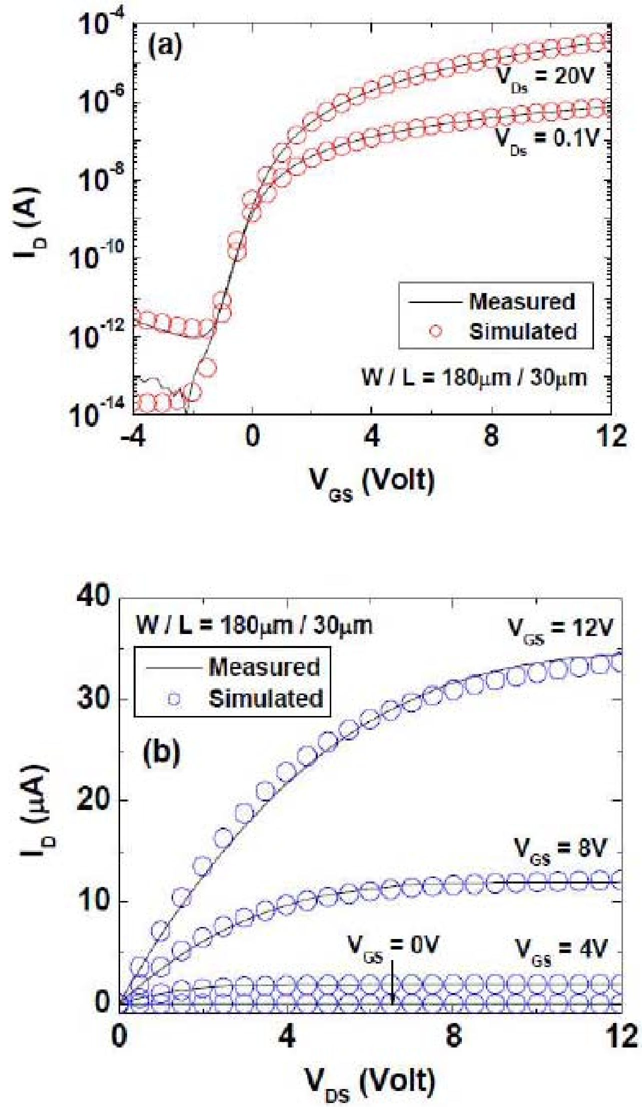


**Figure 1 Measured and simulated (a) transfer and (b) output characteristics of a-InGaZnO TFT. Simulation is performed by HSPICE.**

## 2. a-InGaZnO TFT Model Extraction

a-InGaZnO TFT SPICE model was developed based on the Rensselaer Polytechnic Institute (RPI) a-Si:H TFT model. Needed a-InGaZnO TFT SPICE parameters were extracted from

ISSN 0097-966X/12/4303-1097-$1.00 © 2012 SID

| Device parameters | 2-TFT | Proposed Circuit | |
|---|---|---|---|
| | | a-IGZO | a-Si:H |
| W/L(SW1,SW2,PC) [μm] | 4/4 | 5/5 | 5/60 |
| W/L(MR,DR) [μm] | 4/24 | 5/5 | 5/60 |
| $C_{ST1}$ [pF] | 1 | 0.22 | 0.22 |
| $C_{ST2}$ [pF] | N/A | 0.04 | 0.04 |
| $C_{GS}$, $C_{GD}$ [fF/m] | 10 | 10 | 10 |
| **Supplied signals** | | | |
| $V_{DD}$ [V] | 10 | 10 | 20 |
| $V_{DATA}$ [V] | 3 → 9 | 0 → 4.4 | 5 → 11 |
| $V_{GATE2}$[n-1] [V] | N/A | -5 → 15 | -10 → 30 |
| $V_{GATE2}$[n] [V] | N/A | -5 → 15 | -10 → 30 |
| $V_{GATE1}$[n] [V] | -1 → 10 | -5 → 15 | -10 → 30 |
| **Time frames** | | | |
| $t_{ox}$ [ms] | 0.04 | 0.04 | 0.04 |
| $t_{off}$ [ms] | 16.7 | 16.7 | 16.7 |

**Table 1 Device and Circuit Parameters based on a-InGaZnO TFT and a-Si:H TFT for SPICE Simulation**

experimental data. HSPICE simulation tool was then used to simulate the TFT characteristics (illustrated as the open circles in Fig. 1). We can see that the RPI a-Si:H TFT model with appropriate a-InGaZnO TFT SPICE parameters can reproduce very well our measured device characteristics. SPICE parameters were extracted based on experimental data reported in [6, 7], and summarized in Table 1. The OLED area was assumed to be 4563μm$^2$ which is about the subpixel area of an RGB 4.3" WVGA display (39μm x 117μm). The OLED capacitor was calculated by assuming the capacitance per unit area is 25nF/cm$^2$. The electrical behavior of the OLED was modeled with two junction diodes and two series resistors connected in parallel with a capacitor for the simulation.

## 3. Results and Discussions

### 3.1 Pixel Circuit Configurations

In this paper, all reported AM-OLEDs driven by a-InGaZnO TFTs are based on the 2-TFT voltage-programmed pixel circuit. The 2-TFT voltage-programmed pixel circuit is very simple in design and enables a high aperture ratio. However, since this simple circuit does not compensate for the TFT threshold voltage variation ($\Delta V_{TH}$), the usage of this circuit requires the TFTs to be electrically very stable ($\Delta V_{TH}$ ~ 0). Authors have previously explored the possible application of a-InGaZnO TFTs to a current scaling pixel circuit that provides a wide dynamic OLED current ($I_{OLED}$) range and compensation abilities [8]. Here, we apply a-InGaZnO TFTs to a voltage-programmed pixel electrode circuit that has shown some enhancement with a-Si:H TFT[9]. Synopsys HSPICE simulation tool with the a-InGaZnO TFT and OLED

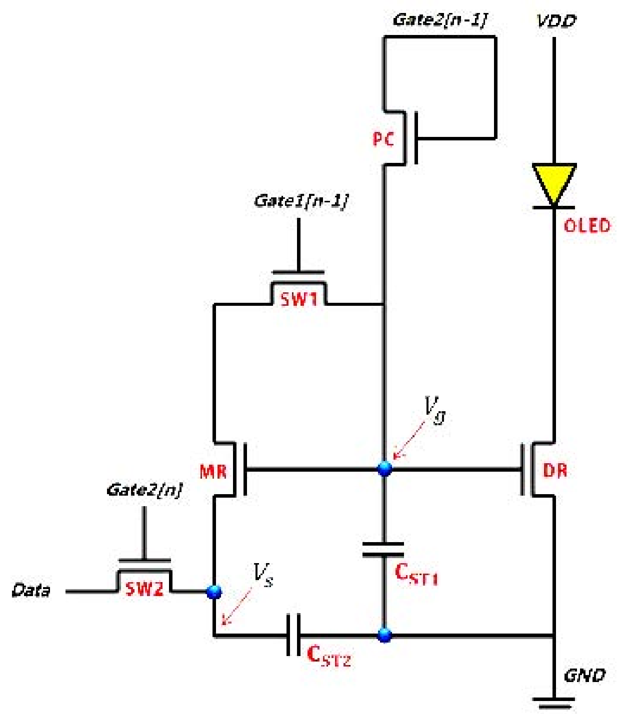


**Figure 2 Schematic diagram of the proposed voltage-programmed pixel circuit.**

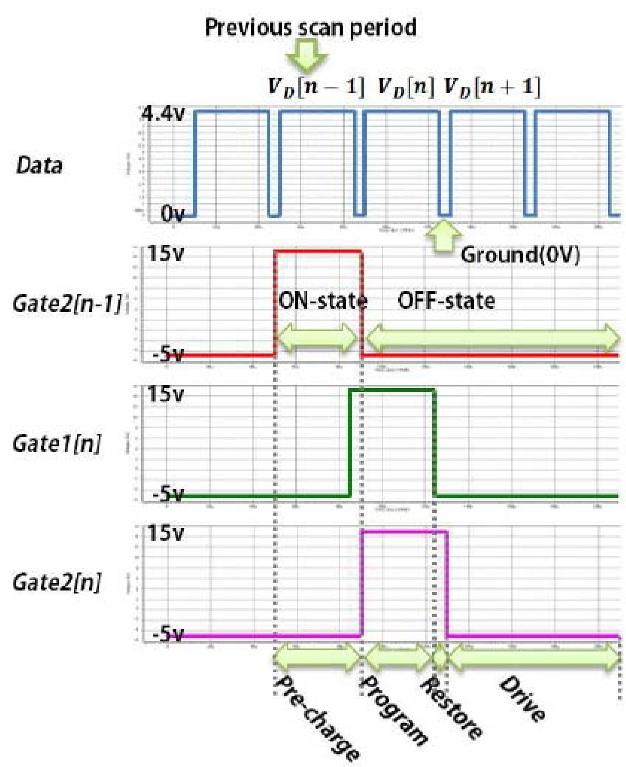


**Figure 3 Operation waveforms of the proposed pixel circuit simulated by HSPICE**

SPICE models developed previously were used to evaluate the pixel circuit performance. As shown in Figure 2, each pixel is composed of one power line ($V_{DD}$), two control lines (Gate1, Gate2), two capacitors ($C_{st1}$, $C_{st2}$), and five TFTs; two switch TFTs (SW1, SW2), a pre-charge TFT (PC), a drive TFT (DR), and a mirror TFT (MR). The operation detail of this circuit can be found elsewhere [9]. Since the field-effect mobility of a-InGaZnO TFTs is about 10 times larger than that of a-Si:H TFTs, smaller device sizes (W/L = 5μm/5μm) and lower supply voltages ($V_{DD}$ = 10V) can be used for this circuit based on a-InGaZnO TFTs. The pixel circuit operates in four stages; pre-charge, program, restore, and drive. An example of operation waveforms simulated by HSPICE is shown in Fig. 3.

### 3.2 Simulation Results

The OLED currents ($I_{OLED}$) delivered by the 2-TFT voltage-programmed pixel circuit and by the proposed 5-TFT voltage-programmed pixel circuit with compensation capability as a function of $V_{DATA}$ are shown respectively in Fig. 4 (a). When the frame rate is set to be 60Hz, $t_{ON}$ (40μs) and $t_{OFF}$ (16.7ms) are the ON- and OFF-state periods, respectively. As we can see from Fig. 4, wide dynamic $I_{OLED}$ range (~$10^3$) was achieved by both pixel circuits. We also simulated the two pixel circuits assuming that the drive TFTs exhibit 1 and 2V of threshold voltage shifts ($\Delta V_{TH}$), as shown in Fig. 4 (a). The percentage change in $I_{OLED}$ ($\Delta I_{OLED}$) is defined as following,

$$\Delta I_{OLED} = \frac{I_{OLED}(\Delta V_{TH} = 0) - I_{OLED}(\Delta V_{TH})}{I_{OLED}(\Delta V_{TH} = 0)} \quad (1)$$

We can see that the proposed 5-TFT voltage-programmed pixel circuit can compensate for $\Delta V_{TH}$ within operating error range from 1 to 19%, depending on the $I_{OLED}$ level, while the 2-TFT voltage-programmed pixel circuit does not compensate for $\Delta V_{TH}$ at all ($\Delta I_{OLED}$: 40~90%). Keeping in mind that 1V of $\Delta V_{TH}$ is quite large comparing to the small gate overdrive (0~5V) designed to be used in the pixel circuit simulations, this result indicates that we need electrically very stable a-InGaZnO TFTs to be used in the 2-TFT pixel electrode circuit for AMOLEDs. To further investigate the compensation ability of the 5-TFT voltage-programmed pixel circuit, we plotted $\Delta I_{OLED}$ as a function of $I_{OLED}$ for positive $\Delta V_{TH}$ = 0.5V, 1.5V, and 2.0V, as shown in Fig. 4 (b). We can observe that $\Delta I_{OLED}$ is severe at lower $I_{OLED}$ levels due to the smaller gate overdrive of the drive TFT. The percentage error can be maintained below 20% for all levels of $I_{OLED}$ as long as positive $\Delta V_{TH}$ is kept below 2.0V, which is acceptable operation range for commercial products.

### 4. Conclusion

We fabricated and characterized inverted-staggered a-InGaZnO TFTs on glass substrates, and SPICE model was developed based on experimental data. Both simple voltage-programmed pixel circuits and 5-TFT voltage-programmed pixel circuits with $\Delta V_{TH}$ compensation ability were simulated. Smaller device sizes and lower supply voltages could be used in a-InGaZnO TFT pixel circuits due to their superior electrical properties compared to those of a-Si:H TFTs. The simple voltage-programmed pixel circuits could be used provided that the a-InGaZnO TFTs are electrically very stable ($\Delta V_{TH}$ ~ 0V). Otherwise, 5-TFT voltage-programmed pixel circuit is needed to compensate for $\Delta V_{TH}$. It is shown that our 5-TFT voltage-programmed pixel circuit can compensate $\Delta V_{TH}$ under bias stress conditions below 20%. In conclusion, a-InGaZnO TFTs, if fully optimized, have great potential for higher resolution, lower power consumption, and more stable operation AM-OLEDs.

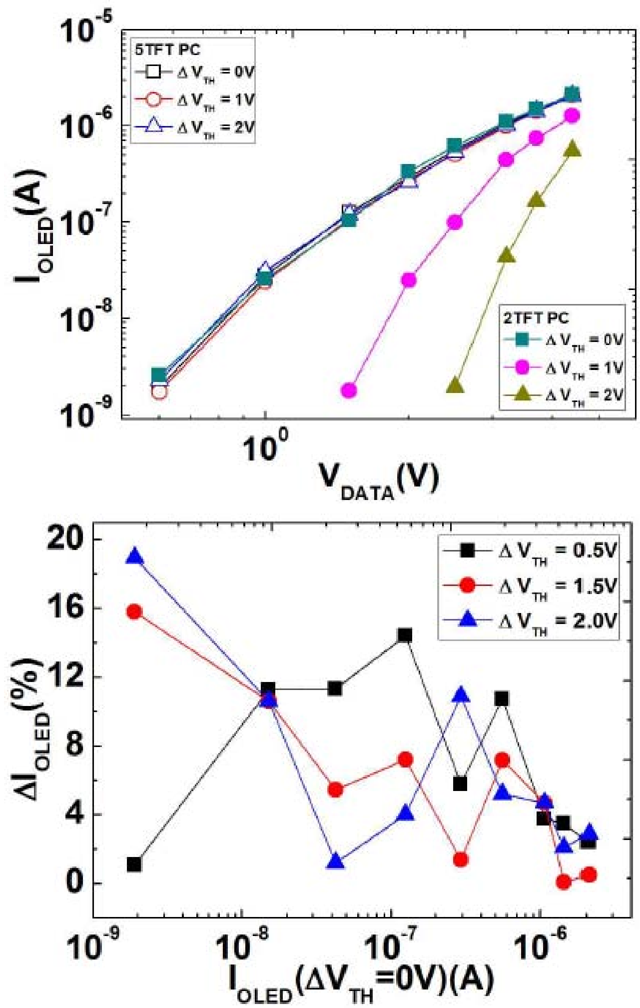


**Figure 4 (a) $I_{OLED}$ as a function of $V_{DATA}$ of the 2-TFT pixel circuit (solid symbols), and our proposed 5-TFT pixel circuit (open symbols). (b) $\Delta I_{OLED}$ as a function of $I_{OLED}$ of the proposed voltage-programmed pixel circuit for various levels of $\Delta V_{TH}$.**


### 5. Acknowledgements

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2011-0013336).

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