P-14: AM-OLED Pixel Circuits Based on a-InGaZnO Thin Film Transistors

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Abstract

In this paper, we investigated the application of amorphous In-Ga-Zn-O (a-InGaZnO) thin film transistors (TFTs) to active-matrix organic light emitting display (AM-OLED) pixel circuits. SPICE model of a-InGaZnO TFTs was developed based on experimental data. Several pixel circuits were explored, and the potential advantages of using a-InGaZnO TFTs were discussed.

1. Introduction

Active-matrix organic light-emitting display (AM-OLED) is now generally viewed as the next generation display because of its vivid color, high contrast ratio, thin/light display module, and low energy consumption [1]. 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, the insufficient field-effect mobility and metastable shift in threshold voltage when subject to prolonged gate bias [2] make their application to AM-OLEDs rather difficult. (In AM-OLEDs, the drive TFT has to constantly supply a current to the organic light-emitting diode (OLED) instead of just acting like a switch.) Larger devices and more complex pixel circuits are needed to realize a-Si:H TFT AM-OLEDs, which greatly limits the display resolution. As a result, TFTs based on other semiconductor materials have been explored as an alternative approach [3]-[5]. 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 [5]. Several voltage-programmed a-InGaZnO TFT AM-OLEDs have been demonstrated by other groups, indicating a promising future for these devices [6][7]. In this paper, a-InGaZnO TFT SPICE model was developed based on experimental data. We simulated several voltage- and current-programmed a-InGaZnO TFT pixel circuits and analyzed their advantages over a-Si:H TFT pixel circuits.

2. Experimental

The a-InGaZnO TFTs were fabricated on glass substrates. The gate electrode Ti (5nm)/Au (40nm)/Ti (5nm) was deposited by electron-beam and patterned by lift off. The gate insulator SiO_2 (200nm) and a-InGaZnO thin film were both deposited by RF sputtering and patterned by wet etch. After annealing in air at 300°C for 20 min, the source/drain electrodes Ti (5nm)/Au (100nm)/Ti (5nm) were deposited by electron-beam and patterned by lift off. A SiO_2 film as the back channel protection layer (100nm) was deposited by RF sputtering and patterned by wet etch. Finally, the TFTs were annealed in air at 200°C for 1 hour [8]. Electrical measurements were done in dark using a Hewlett-Packard 4156A semiconductor parameter analyzer. The measured TFT transfer and output characteristics are shown in Fig. 1. The a-InGaZnO TFTs exhibit very low off- current, sharp subthreshold swing (0.4V/dec), threshold voltage (V_T) ~3V, and field-effect mobility (μ) ~10cm^2/V-s. The V_T and μ were extracted from linearly fitting the I_D-V_{GS} curve to the standard MOSFET equation. The fitting range was chosen to be between 10% and 90% of the maximum measured I_D (V_{GS} = 20V) [9].

3. a-InGaZnO TFT and OLED SPICE Model

a-InGaZnO TFT SPICE model was developed based on the Rensselaer Polytechnic Institute (RPI) a-Si:H TFT model [10]. Needed a-InGaZnO TFT SPICE parameters were extracted from 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.

To model the behavior of the OLED, we used two junction diodes D_1 D_2 (HSPICE diode model level 1) with series resistors R_{S1} R_{S2}

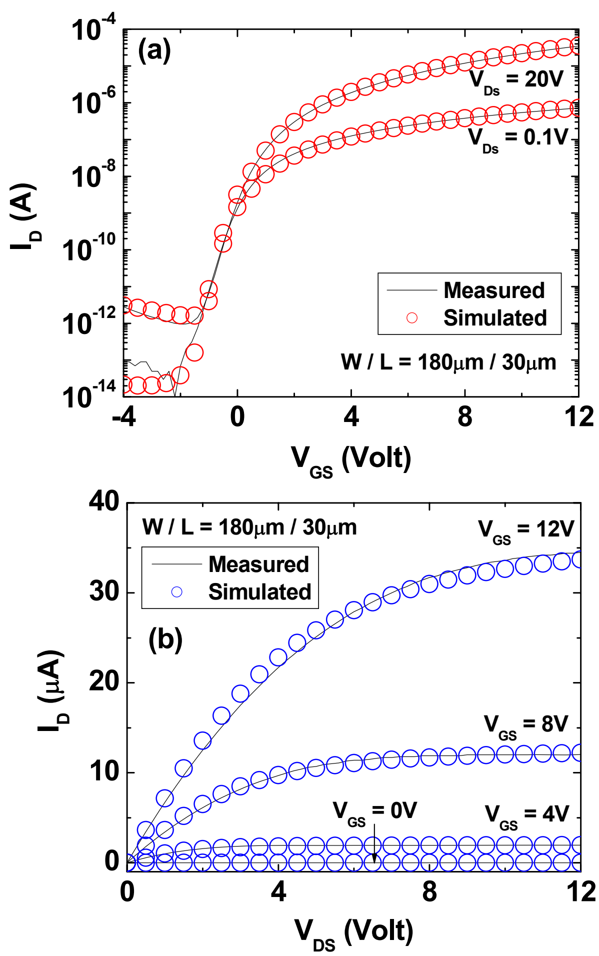

Figure 1. Measured and simulated (by HSPICE) a-InGaZnO TFT (a) transfer characteristics and (b) output characteristics.

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connected in parallel with a capacitor C, shown as the inset of Fig. 2. SPICE parameters were extracted based on experimental data obtained within our group [11], and summarized in Table 1. The OLED area was assumed to be 12000μm^2 which is about the subpixel area of an RGB 3" QVGA display (63.5μm x 190.5μm). The OLED capacitor was calculated by assuming the capacitance per unit area is 25nF/cm^2. The OLED I-V curve simulated by HSPICE is shown in Fig. 2.

4. Simple Voltage-Programmed Pixel

So far, all reported AM-OLEDs driven by a-InGaZnO TFTs are based on the 2-TFT voltage-programmed pixel circuit [6][7], as shown in Fig. 3 (a). Since this simple circuit does not compensate for the TFT threshold voltage variation (ΔV_T), the usage of this circuit requires the TFTs to be electrically very stable ($\Delta V_T \sim 0$). Many authors have reported on the good electrical stability of a-InGaZnO TFTs [12][13]. Our group also performed current temperature stress (CTS) studies on the a-InGaZnO TFTs [14]. Although some threshold voltage shift was observed, the amount of shift was small compare to that of a-Si:H TFTs [2]. The field-effect mobility, off-current, and subthreshold slope almost remained the same during the stress. Recently, it has been shown that the electrical stability of a-ZnSnO TFTs is highly dependent on the Zn/Sn ratio [15]. We therefore believe it is possible that the electrical stability of a-InGaZnO TFTs can be further improved by optimizing the film chemical composition. Synopsys HSPICE simulation tool with the a-InGaZnO TFT and OLED SPICE models developed in our group were used to evaluate the pixel circuit performance. The simulated operation waveforms are shown in Fig. 4 (a). Parameters used in the simulation are summarized in Table 2. Since the field-effect mobility of a-InGaZnO TFTs is ~10 times larger than that of a-Si:H TFTs, smaller device sizes (W/L = 24μm/4μm) and lower supply voltages (V_{DD} = 10V) can be used in this circuit.

Table 1. OLED SPICE Parameters

Area	12000 μm^2
D1	I_S = 4.2nA, n = 7.8, I_K = 13A
D2	I_S = 60fA, n = 3.6, I_K = 32mA
R_{S1}	2.6mΩ
R_{S2}	27mΩ
C	3pF

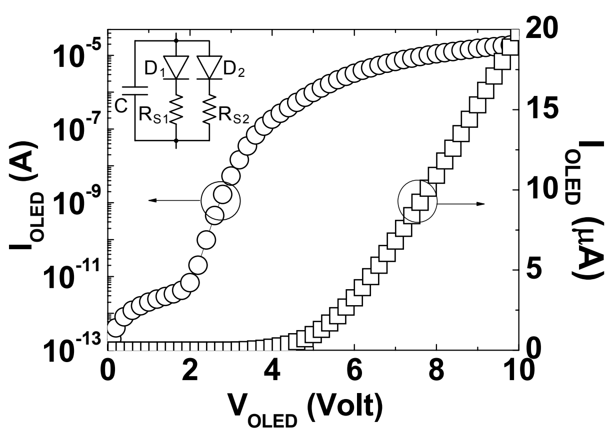

Figure 2. Simulated OLED I-V characteristics

An additional TFT can be added to this circuit to prevent a sudden peak current from damaging the OLED, as shown in Fig. 3 (b). The simulated operation waveforms are shown in Fig. 4 (b). This circuit operates similar as the 2-TFT circuit except the current flows through the OLED only during the expose period.

5. Current-Scaling Current-Mirror Pixel

The 2-TFT voltage-programmed pixel circuit is very simple in design and enables a high aperture ratio. However, due to the current-driven nature of OLEDs and their steep I-V characteristics, current-programmed pixel circuits are more suitable to precisely generate distinct grey levels. Moreover, even if the a-InGaZnO TFTs are electrically very stable, it is still desirable to use a pixel circuit that can compensate for any non-ideal factors. Several current-programmed pixel circuits were developed for AM-OLEDs [16]-[18]. Our group has 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 [19]. Here, we apply a-InGaZnO TFTs to a current-scaling current-mirror pixel circuit [20]. This circuit has

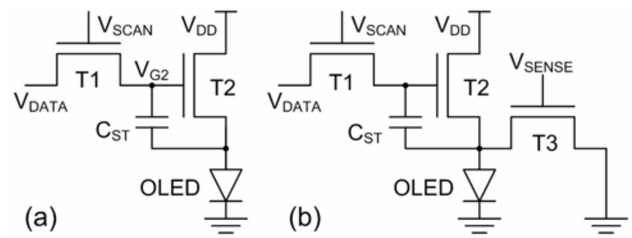

Figure 3. Schematic diagram of the (a) 2-TFT voltage-programmed pixel circuit and (b) the same circuit with an additional TFT (T3).

Table 2. Parameters used in HSPICE simulation

	(a)	(b)		(a)	(b)
T1	4/4		**V_{DD} (V)**	10	8
T2	24/4		**V_{SCAN} (V)**	-1→10	-1→8
T3	NA	8/4	**V_{SENSE} (V)**	NA	-1→8
C_{ST}	1pF		**V_{DATA} (V)**	3 ~ 9	1 ~ 7

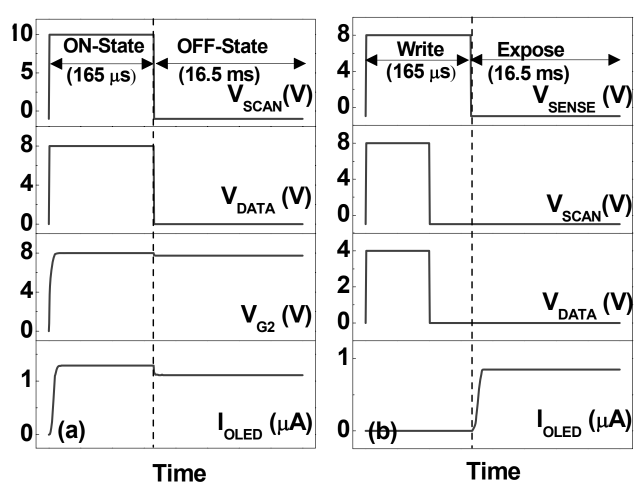

Figure 4. Operation waveforms of the pixel circuits in Fig. 3(a), and (b), respectively, simulated by HSPICE.

similar performance as the previous circuit with a simpler driving scheme. The current-scaling current-mirror pixel circuit consists of two switching TFTs (T1 and T2), one mirror TFT (T4), one driving TFT (T3), and two storage capacitors (C_{ST1}, C_{ST2})connected between the scan line and ground with a cascade structure, as shown in Fig. 5. The operation detail of this circuit can be found elsewhere [20]. Parameters used to simulate this circuit are listed in Table 3 for both a-InGaZnO TFTs and a-Si:H TFTs [20]. Smaller device sizes (W/L = 20μm/4μm) and lower supply voltages (V_{DD}= 12V) can be used for this circuit based on a-InGaZnO TFTs. An example of operation waveforms simulated by HSPICE is shown in Fig. 6.

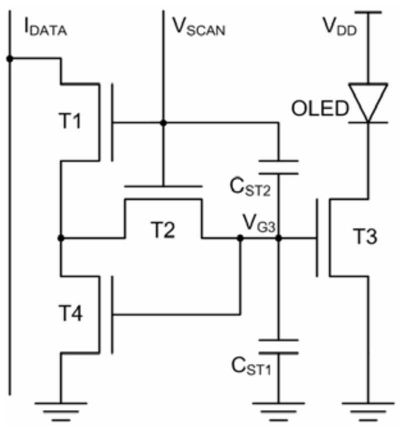

Figure 5. Schematic diagram of the 4-TFT current-scaling current mirror pixel circuit.

Table 3. Parameters used in HSPICE simulation

	a-InGaZnO	a-Si:H [20]
T1, T3, T4	20/4	150/6
T2	4/4	10/6
C_{ST1} (fF)	360	
C_{ST2} (fF)	60	
V_{DD} (V)	12	18
V_{SCAN} (V)	-1→12	-5→25
I_{DATA} (μA)	0.2 ~ 5	

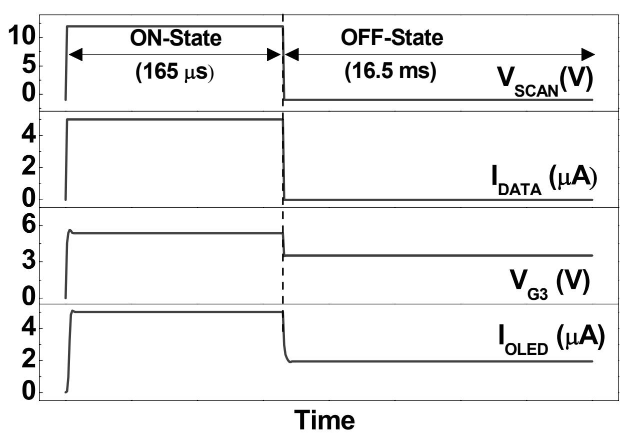

Figure 6. Operation waveforms of the current-scaling current mirror pixel circuit simulated by HSPICE.

6. Pixel Circuit Simulation Results

The OLED currents (I_{OLED}) delivered by the 2-TFT voltage-programmed pixel circuit and the 4-TFT current-scaling current-mirror pixel circuit as a function of V_{DATA} and I_{DATA}, respectively, are shown in Fig. 7. Since the OLED current value is different during the ON- and OFF-states (I_{OLED_ON} and I_{OLED_OFF}), we define the average OLED current (I_{OLED}) during one frame time as

$$I_{OLED} = \frac{I_{OLED\_ON}\cdot t_{ON} + I_{OLED\_OF}\cdot t_{OFF}}{t_{ON} + t_{OFF}} \qquad (1)$$

where t_{ON} (165μs) and t_{OFF} (16.5ms) are the ON- and OFF-state periods, respectively (the frame rate is set to be 60Hz). As we can see from Fig. 7, 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 (T2 in Fig. 3(a), T3 and T4 in Fig. 5) exhibit 1V of threshold voltage shift (ΔV_T), as shown in Fig. 7. The percentage change in I_{OLED} (ΔI_{OLED}) is defined as

$$\Delta I_{OLED} = \frac{I_{OLED}(\Delta V_T = 0) - I_{OLED}(\Delta V_T)}{I_{OLED}(\Delta V_T = 0)}\cdot 100\% \qquad (2)$$

We can see that the 4-TFT current-scaling current-mirror pixel circuit can compensate for ΔV_T within operating error range from 9 to 25%, depending on the I_{OLED} level, while the 2-TFT voltage-programmed pixel circuit does not compensate for ΔV_T at all (ΔI_{OLED}: 40~90%). Keeping in mind that 1V of ΔV_T is quite large comparing to the small gate overdrive (0~5V) designed to be used in the pixel circuit simulations. To further investigate the compensation ability of the 4-TFT current-scaling current-mirror pixel circuit, we plotted ΔI_{OLED} as a function of I_{OLED} for ΔV_T = 0.2V, 0.5V, and 1V, as shown in Fig. 8. We can observe that ΔI_{OLED} is more severe at lower I_{OLED} levels due to the smaller gate overdrive of the drive TFT. The percentage error can be maintained below 10% for all levels of I_{OLED} if ΔV_T is smaller than 0.2V. This result indicates that we need electrically very stable a-InGaZnO TFTs to be used for AM-OLEDs.

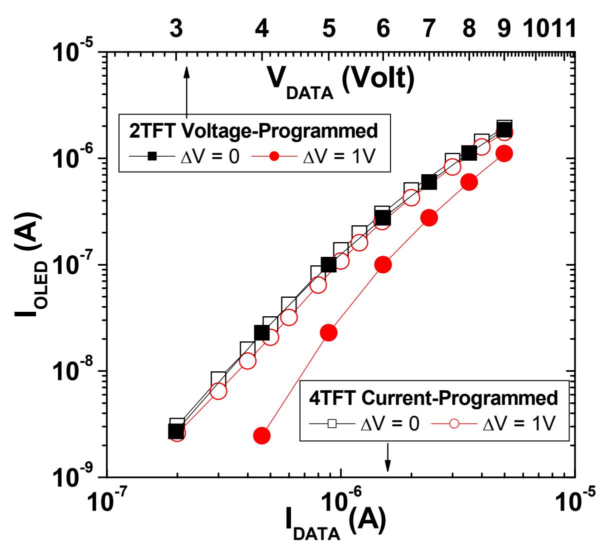

Figure 7. I_{OLED} as a function of V_{DATA} of the 2-TFT voltage-programmed pixel circuit (solid symbols), and I_{DATA} of the 4-TFT current-scaling current-mirror pixel circuit (hollow symbols).

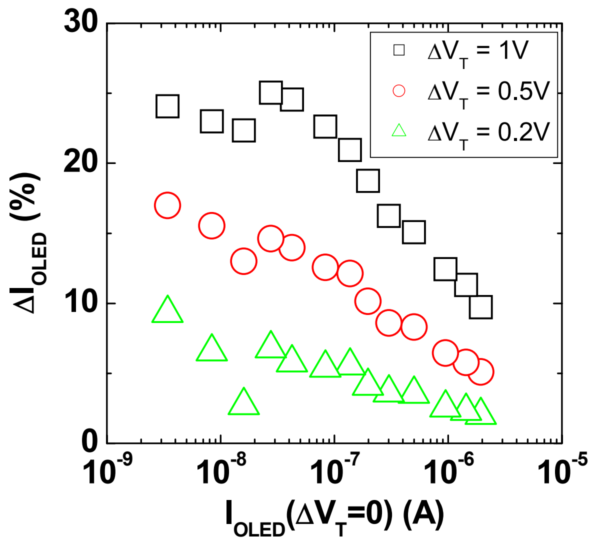

Figure 18. ΔI_{OLED} as a function of I_{OLED} of the 4-TFT current-scaling current-mirror pixel circuit for several levels of ΔV_T.

7. Conclusion

We fabricated and characterized inverted-staggered a-InGaZnO TFTs on glass substrates. SPICE model was developed based on experimental data. Both simple voltage-programmed pixel circuits and current-programmed pixel circuits with ΔV_T 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 voltage-programmed pixel circuits could be used provided that the a-InGaZnO TFTs are electrically very stable (ΔV_T ~0V). Otherwise, the current-programmed pixel circuit is needed to compensate for ΔV_T. In conclusion, a-InGaZnO TFTs, if fully optimized, have great potential for higher resolution, lower power consumption, and more stable operation AM-OLEDs.

8. Acknowledgements

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