3-TFT OLED Pixel Circuit for High Stability with In-pixel Current Source

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Abstract

A new 3-TFT voltage-programmed pixel circuit with an in-pixel current source is presented, which can be largely insensitive to the TFT threshold voltage shift. The fabricated pixel circuit provides OLED current ranging from 25nA to 2.9μA, an on/off ratio of 116 at typical QVGA display timing.

Author Keywords

3-TFT, Voltage-programmed, in-pixel current source, threshold voltage shift compensation, AMOLED pixel circuit

1. Introduction

Active-matrix organic light-emitting diode (AMOLED) displays require highly-stable TFTs that operate in DC to provide constant current over time. The critical issue of stability limits the application of TFT technologies in AMOLEDs, such as the amorphous silicon (a-Si) TFTs [1]. In a traditional 2-TFT pixel circuit [2], the positive threshold voltage shift (ΔV_{th}) of the driving a-Si TFT under gate bias leads to reduced drain current and thereby reduced OLED brightness. Pixel circuits that can compensate for a threshold voltage shift have been introduced as an alternative method to overcome the instability issue of TFTs [3]. Current-programmed methods which use current input data are the one of major compensation methods [4, 5]. However, the current-programmed methods have the drawbacks of a long settling time at low data currents because of the parasitic capacitance of data lines and inconvenient constant current sources that control submicrometer ampere-level current in peripheral drivers [6]. Voltage-programmed methods proposed generally either require an excessive number of TFTs, or complex driving scheme.

In this work, we present a new 3-TFT voltage-programmed pixel circuit with an in-pixel current source. By using a TFT which operates at ~0.1% duty cycle to translate the programming voltage to a pixel current, the pixel current can be made largely insensitive to the threshold voltage shift of the driving TFT. Further, we fabricated and characterized the new 3-TFT driving pixel with a-Si TFT technology and demonstrate that its dynamic range of driving current is greater than 100 under QVGA timing.

2. Pixel circuit operation

Fig. 1 illustrates the schematic circuit of the 3-TFT pixel circuit. This pixel circuit consists of a switching TFTs (T_1), a driving TFT (T_2), a programming TFT (T_3), a storage capacitor (C_s) and an OLED. The control signal lines are three row lines (V_{sel0}, V_{sel1} and V_{sel2}). The data line is the column line (V_{data}). The ground (GND) of the OLED is a blanket cathode shared by all the pixels.

During a frame time, the pixel operates in two modes – programming mode during the row time and emission mode otherwise. In the programming mode, V_{sel0} and V_{sel2} are set to high and V_{sel1} is set to low, so T_1 and T_3 are turned on. Since V_{sel0} is set to high, T_2 can be considered to be operating in diode mode with gate and drain connected through T_1. V_{sel1} is set to be low enough to ensure that OLED is reverse-biased and remains turned off during programming. The simplified circuit in programming mode can be shown as Fig. 2 (a). T_3 is in saturation, acting as a local current source to set the pixel current in T_2 by its gate-source voltage, which is the voltage difference between V_{sel2} and V_{data}. The gate-source voltage V_{GS} of T_2 will adjust itself to mirror the current programmed into T_3, and the relevant V_{GS} of T_2 will be stored on capacitor C_s at the end of the programming cycle.

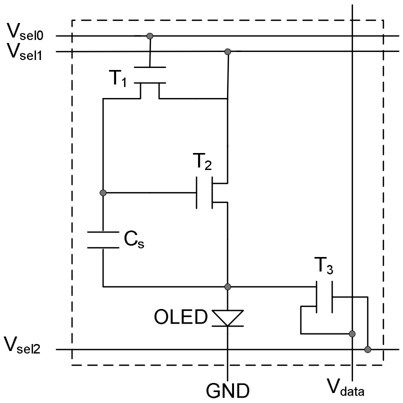
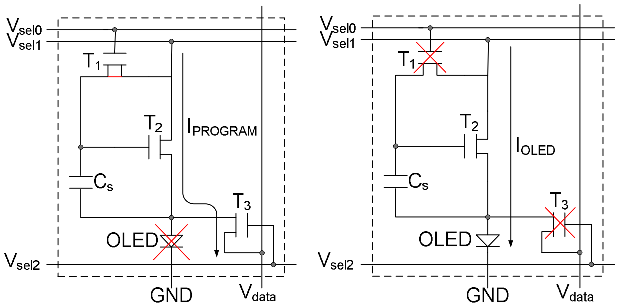
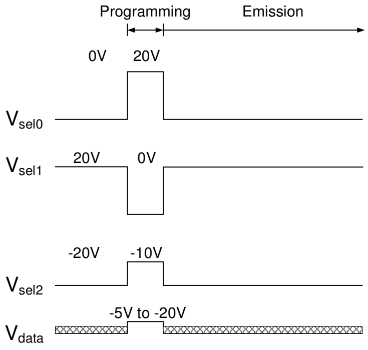


Figure 1. Schematic pixel circuit.



(a) programming mode (b) emission mode



(c) controlling signals

Figure 2. Simplified circuits in programming mode and emission mode and controlling signals vs. time.

In the emission mode, V_{sel0} and V_{sel2} are set to low and V_{sel1} is set to high. T_1 is turned off to hold the gate-source voltage on OLED driver T_2. T_3 is also turned off so that the current supplied by T_2

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flows through the OLED and controls its brightness. The simplified circuit in emission mode is shown as Fig. 2 (b). Because the gate-source voltage V_{GS} of T_2 established during the programming mode can be held by C_s, the drain current passing through T_2 remains the same as that in the programming mode, if we ignore the channel length modulation effect. This effect is relevant because during programming the drain-source voltage of T_2 is equal to its gate-source voltage (at the onset of saturation), but during emission mode T_2 will be father into saturation with a higher drain voltage.

Note that T_2 is in DC operation providing current to the OLED during the emission mode, and hence prone to the threshold voltage shift. T_3, which converts the applied voltage (V_{sel2} - V_{data}) into the pixel current, is only positive-biased in programming mode at a low duty cycle (<0.1%), and its threshold voltage can recover during the emission mode. The threshold voltage of T_3 is expected to be far more stable than that of T_2. In the new 3-TFT pixel circuit, T_2 is effectively "current programmed" on each frame time, so that the pixel current is insensitive to the threshold voltage shift of the driving TFT T_2. Thus the pixel should be highly stable compared to the conventional 2-TFT voltage-programmed pixel.

3. Pixel circuit fabrication and characterization

The pixel circuit was fabricated with standard back-channel passivated (BCP) a-Si TFT technology on a glass substrate [7]. Fig. 3 shows the cross-section of the TFT structure in the circuit.

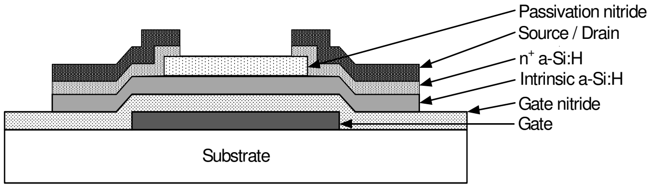

Figure 3 Schematic cross-section of back-channel passivated TFT structure.

Typical isolated TFT transfer characteristics are demonstrated in Fig. 4. In the saturation regime, the threshold voltage is 0.4V, the field-effect mobility is $0.9cm^2/V \cdot s$ and the subthreshold slope is 500mV/dec.

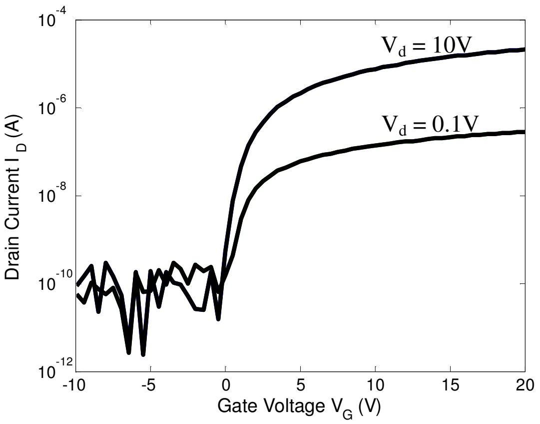

Figure 4 Transfer characteristics of a typical isolated TFT with W/L = 150/15µm.

For testing purposes, the OLED in the pixel circuit (Fig. 1) was replaced with a diode-connected TFT (T_4) in combination with a capacitor (C_{OLED}) in parallel. The circuit design parameters are listed in Table 1. Large voltage swings (-10V to 20V) were used on the row lines to simplify testing – smaller swing would be used in practice.

Table 1. Circuit design and testing parameters

Name	Value
V_{sel0} (V)	0 to 20
V_{sel1} (V)	20 to 0
V_{sel2} (V)	-20 to -10
V_{data}(V)	-5 to -20
T_1 (W/L) (µm)	20/15
T_2 (W/L) (µm)	150/15
T_3 (W/L) (µm)	150/15
T_4 (W/L) (µm)	150/15
C_s (pF)	3.5
C_{OLED} (pF)	10

The DC operation of the pixel circuit in programming mode was confirmed by holding V_{sel0} = 0V, V_{sel1} = 20V, V_{sel2} = -10V. The programmed OLED current was measured as a function of V_{data} under DC and plotted with the blue curve in Fig. 5.

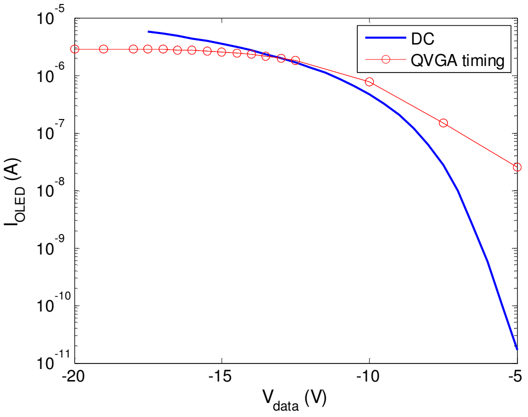

Figure 5. OLED current vs. V_{data} in both DC and QVGA timing operation.

The exponential dependence of the programmed OLED current on V_{data} at high V_{data} range reflects the subthrehold operation of T_3. The slope of 600mV/dec from Fig. 5 is in good qualitative agreement with that of the test TFT characteristics (500mV/dec) shown in Fig. 4.

Under the typical display QVGA timing (50µs programming time and 16ms frame time) and V_{data} = -15V, the OLED current was measured. The measured transient waveform is shown in Fig. 6. During the 16ms frame time, the OLED current holds at its programmed value 2.55µA.

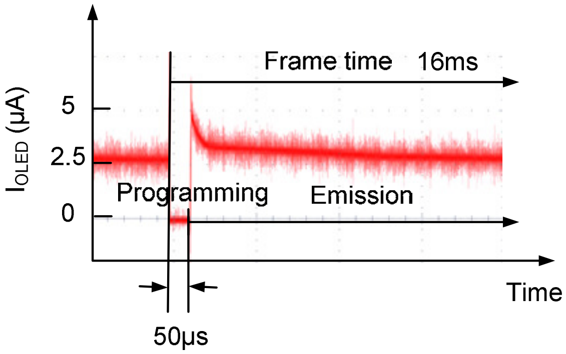

Figure 6. Transient waveform of OLED current.

Under the same QVGA timing conditions, the OLED current in emission mode was also measured as a function of V_{data} (red circles in Fig. 5). Fig. 5 shows that the pixel circuit can provide OLED current ranging from 25nA to 2.9µA, which gives an on/off ratio of 116 at typical QVGA display timing. This is a very high dynamic range compared with typical current-programmed methods, which have limitations at low current level [6]. The settling time in conventional current-programmed pixel circuits, depends on the capacitance of the data line, which includes the gate-source/drain overlaps in all rows. In the new 3-TFT pixel circuit, the relevant capacitors are that of the OLED and the storage capacitor C_s, independent of the parasitic capacitance of data lines.

In Fig. 5, the current at QVGA timing is higher than that in DC for the low current range, in part because the gate-drain overlap capacitance of T_2 pulls up its gate voltage when V_{sel1} is set to high at the beginning of emission mode. Note that a high voltage supply range (0V - 20V) was used for V_{sel1} for simplified initial characterization of the circuit performance. With lower supply voltage range in practice in AMOLED displays, this effect should be reduced.

4. Stability analysis

Ideally, without considering the channel length modulation and transient effect, any threshold voltage shift of T_2 does not affect the pixel current determined by the voltage difference between V_{sel2} and V_{data} in the programming mode. However, a-Si TFTs have a channel length modulation effect, and the threshold voltage shift of T_2 affects the V_{DS} of T_2 and T_3, which leads to the programmed OLED current drop.

We modeled this effect with circuit simulator. The programmed OLED current drop was simulated as a function of the threshold voltage shift for T_2 with a channel length modulation coefficient of 0.01 for all the TFTs. In DC programming mode with V_{sel0} = 0V, V_{sel1} = 20V, V_{sel2} = -10V and V_{data} = -15V, the programmed OLED current drop vs. ΔV_{th} of the driving TFT T_2 is demonstrated in Fig. 7, where the OLED current is normalized to the initial OLED current when ΔV_{th} is zero.

Fig. 7 suggests that the programmed OLED current drop is smaller than 5%, for a 5V threshold voltage shift of the driving TFT T_2. Thus, the new 3-TFT voltage-programmed pixel circuit with in-pixel current source can be largely insensitive to the TFT threshold voltage shift.

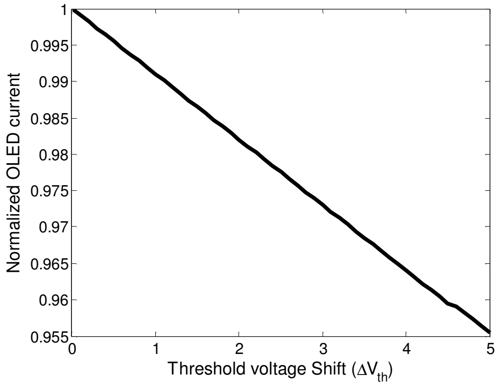

Figure 7. Simulated OLED current drop vs. ΔV_{th} of driving TFT T_2.

5. Conclusion

A new 3-TFT voltage-programmed pixel circuit with in-pixel current source was presented. The circuit combines the speed advantage of voltage-programming in large pixel arrays with the ability of current-programming to avoid OLED current drop due to the threshold voltage shift of driving TFTs. With 16ms frame time and 50µs programming time, our experimental results show that the proposed pixel circuits can provide OLED current ranging from 25nA to 2.9µA, which gives an on/off ratio of 116 at typical QVGA display timing. Simulation suggests that the programmed OLED current drop should be smaller than 5%, for a 5V threshold voltage shift of the driving TFT. Thus, the new pixel circuit can be largely insensitive to the TFT threshold voltage shift.

6. References

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