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

Ting Liu and James C. Sturm
Department of Electrical Engineering, and Princeton Institute for the Science and Technology of Materials, Princeton University, Princeton, NJ 08544 USA

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 ($\Delta V_{th}$) 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 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.

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 $T_2$...
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 further 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.](image)

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·s and the subthreshold slope is 500mV/dec.

![Figure 4 Transfer characteristics of a typical isolated TFT with W/L = 150/15µm.](image)

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

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_{sel0} ) (V)</td>
<td>0 to 20</td>
</tr>
<tr>
<td>( V_{sel1} ) (V)</td>
<td>20 to 0</td>
</tr>
<tr>
<td>( V_{sel2} ) (V)</td>
<td>-20 to -10</td>
</tr>
<tr>
<td>( V_{data} ) (V)</td>
<td>-5 to -20</td>
</tr>
<tr>
<td>( T_1 ) (W/L) (µm)</td>
<td>20/15</td>
</tr>
<tr>
<td>( T_2 ) (W/L) (µm)</td>
<td>150/15</td>
</tr>
<tr>
<td>( T_3 ) (W/L) (µm)</td>
<td>150/15</td>
</tr>
<tr>
<td>( C_s ) (pF)</td>
<td>3.5</td>
</tr>
<tr>
<td>( C_{OLED} ) (pF)</td>
<td>10</td>
</tr>
</tbody>
</table>

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.](image)

The exponential dependence of the programmed OLED current on \( V_{data} \) at high \( V_{data} \) range reflects the subthreshold 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.
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 $C_s\prime$, 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. $\Delta V_{th}$ of the driving TFT $T_2$ is demonstrated in Fig. 7, where the OLED current is normalized to the initial OLED current when $\Delta V_{th}$ 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.

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