Current-Source a–Si:H Thin-Film Transistor Circuit for Active-Matrix Organic Light-Emitting Displays

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***Abstract*—In this letter, we describe a four thin-film-transistor (TFT) circuit based on hydrogenated amorphous silicon (a–Si : H) technology. This circuit can provide a constant output current level and can be automatically adjusted for TFT threshold voltage variations. The experimental results indicated that, for TFT threshold voltage shift as large as ~3 V, the output current variations can be less than 1 and 5% for high ($\geq$0.5 μA) and low ($\leq$0.1 μA) current levels, respectively. This circuit can potentially be used for the active-matrix organic light-emitting displays (AM–OLEDs).**

***Index Terms*—Amorphous semiconductors, light-emitting diodes, light-emitting diode displays, thin-film transistors.**

RECENT enhancements of the organic light-emitting devices (OLEDs) luminous efficiency [1], brightness [2], and lifetime [3] have made possible to extend this technology to the active-matrix organic light-emitting displays (AM-OLEDs). Over the last several years, one-TFT [4], two-TFT [6], [7], and four-TFT [5] based circuits have been proposed for AM-OLEDs. Today, it is accepted that continuous excitation during the whole frame period is needed for high-performance AM–OLEDs. This requirement cannot be fulfilled by one-TFT pixel circuit (i.e., one TFT per pixel). The continuous excitation can only be achieved by either the two-TFT or four-TFT pixel circuits. Up to now most of the devices for AM-OLEDs have been based on polycrystalline silicon technology [5]–[7]. Among them, the four-TFT circuit can not only provide a continuous excitation to the OLED during the frame period, but can also partially compensate for the TFTs' threshold voltage instabilities induced by process variation and circuit aging [5].

In this work, we proposed a current-source four-TFT pixel circuit based on amorphous silicon (a–Si : H) technology. This circuit can provide a continuous current flow even after the pixel select line signal is turned off. In addition, in this circuit the TFTs threshold voltage variations can be fully compensated, and consequently a constant current flow can be provided at all times. The proposed circuit can be used for the AM-OLEDs.

Fig. 1(a) and (b) illustrates the equivalent circuit and the top view of the current-source four-TFT pixel circuit. In this circuit, the OLED is represented by a TFT (T5) in combination with a diode capacitance (C_{diode}) in parallel. The T5 and C_{diode} sizes were optimized to ensure that under the forward bias condition the current flow in T5-C_{diode} combination is similar to the one expected for the OLED's. The fabrication process of this four- a-Si:H TFT circuit is comparable to the standard process steps developed for a conventional inverted-staggered back-channel-etch a-Si:H TFT. First, a 1000-Å thick chromium layer was deposited on Corning 1737 glass by sputtering method and patterned to form the TFT gate electrodes and the storage capacitor (C_s) bottom electrode. A-SiNx:H (3000 Å), intrinsic a-Si : H (2000 Å), and n$^+$ a-Si:H (500 Å) layers were then deposited by the plasma-enhanced chemical vapor deposition (PECVD) technique. After the patterning of the active area (a-Si:H island), 2000 Å thick molybdenum was deposited by sputtering method and patterned to form the TFT source-drain electrodes and storage capacitor top electrode. The interconnects between different TFTs were formed at the same time. The TFT back channel is reactive-ion etched (RIE) using the dry etching process. Then, a-Si Nx : H (3000 Å) was deposited on the top to passivate the circuit.

The electrical properties of the circuit were measured using the probe station. The data (constant current, I_{data}) and source line (constant voltage, $V_{DD} = 9$ V) signals were provided by a HP 4156A semiconductor analyzer. The select line signal (pulsed voltage, V_{select}) was provided by a Keithley 237 source-measure unit with an ON voltage = 25 V, OFF voltage = 0 V, and a duty cycle of 10% (ON time: 100 ms, period: 1000 ms). The output current (I_{out}) of this circuit was measured by the HP semiconductor analyzer after the input data current (I_{data}) and source line voltage (V_{DD}) were turned off, i.e., after the pixel circuit is deselected. This will allow to verify the pixel circuit ability to provide a continuous excitation. The sampling of the output current (I_{out}) was triggered by the falling edge of the select pulse voltage signal to ensure that the data is collected after the circuit is turned off. The TFT threshold voltage was deduced from the drain current-gate voltage ($I_{DS} - V_{GS}$) characteristics.

Fig. 1(a) shows the equivalent four–TFT circuit. This circuit has four external terminals: V_{select}, I_{data}, V_{DD}, and ground. The V_{select}, I_{data}, and V_{DD} signals are provided externally, while the OLED cathode is ground terminal. Fig. 1(c) shows an example of the operational waveform that can be used for these signals. The operation of this circuit can be described as follows.

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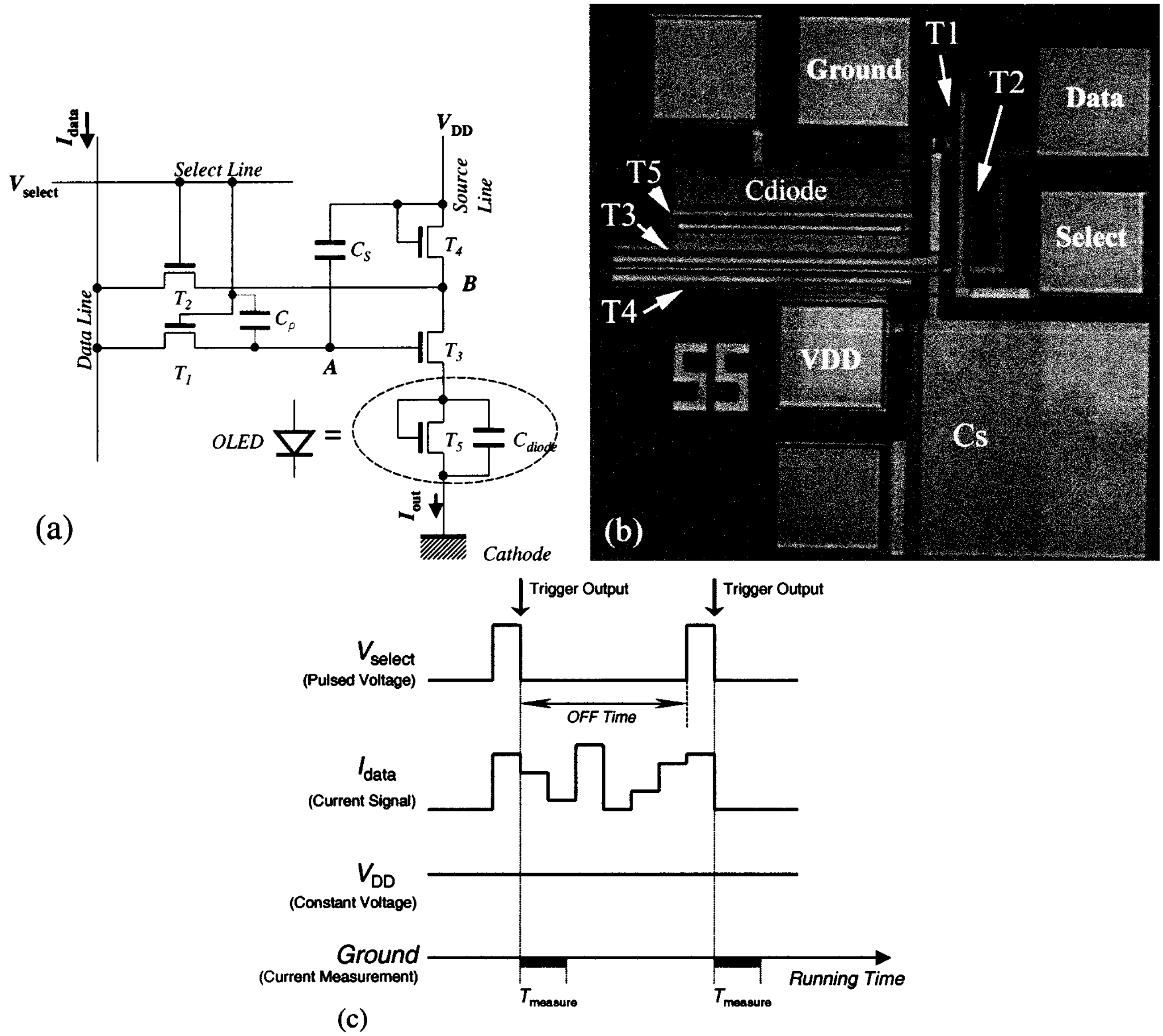

Fig. 1. (a) Equivalent circuit of the constant current-source, 4-TFT pixel circuit and (b) the top view of the circuit are shown. (c) An example of the operation waveforms that can be used for the external terminals is shown. The select line signal is a pulsed voltage with 10% duty cycle (ON time 100 ms, period 1000 ms). The data line signal is current signal that can be adjusted. The source line signal is a constant voltage source. The output current is measured on the OLED ground pad after the select line voltage signal is set low. The measurement time ($T_{measure}$) is typically 2 to 3 ms.

When the select line (V_{select}) signal is high, both T1 and T2 are turned ON. The data line signal (I_{data}) then passes through T1 and T2 and sets both the drain and gate voltages of T3. Consequently, the potentials at nodes A and B will allow the data current (I_{data}) to pass through T3. The T3 is working in the deep saturation region, e.g., $V_{DS} > V_{GS} - V_{th}$ (threshold voltage). The V_{DD} is chosen to be lower than the T3 drain voltage (to ensure that no current can flow through T4 from V_{DD}. Therefore, in this case the current flowing though T3 is equal to I_{data}. This current then will turn on the T5 (e.g., representing OLED) and will reach the ground pad. This is ON state.

When the pixel circuit is deselected and the select line signal is low, both the T1 and T2 are OFF. The T3 gate voltage, however, is maintained high by the charges stored in the storage capacitor C_s during ON state. The drain voltage of T3 will drop very quickly to lower values and consequently T4 will turn on to maintain the same level of the output current (I_{out}). This time the current will flow from the V_{DD} to T3 via T4. If the T3 gate voltage is high and the T3 is in the saturation region, it is expected that $I_{\text{out}} = I_{data}$. This is OFF state.

In automatic adjustment, if the drive TFT (T3) threshold voltage changes and if this change is not larger than the amplitude of V_{select} during the circuit operation,T3 gate voltage needs to be changed accordingly to ensure the same output current level. This is achieved through automatic adjustment by the current signal (I_{data}) during the ON state. Therefore, the gate voltage of T3 is always adjusted to maintain the data current (I_{data}) level at about the same value, regardless of the threshold voltage value. Hence, the local V_{th} variation of the drive TFT will not affect the output current (I_{out}) level. The threshold voltage shift of other TFTs in this circuit will not have a major impact on the output current level,

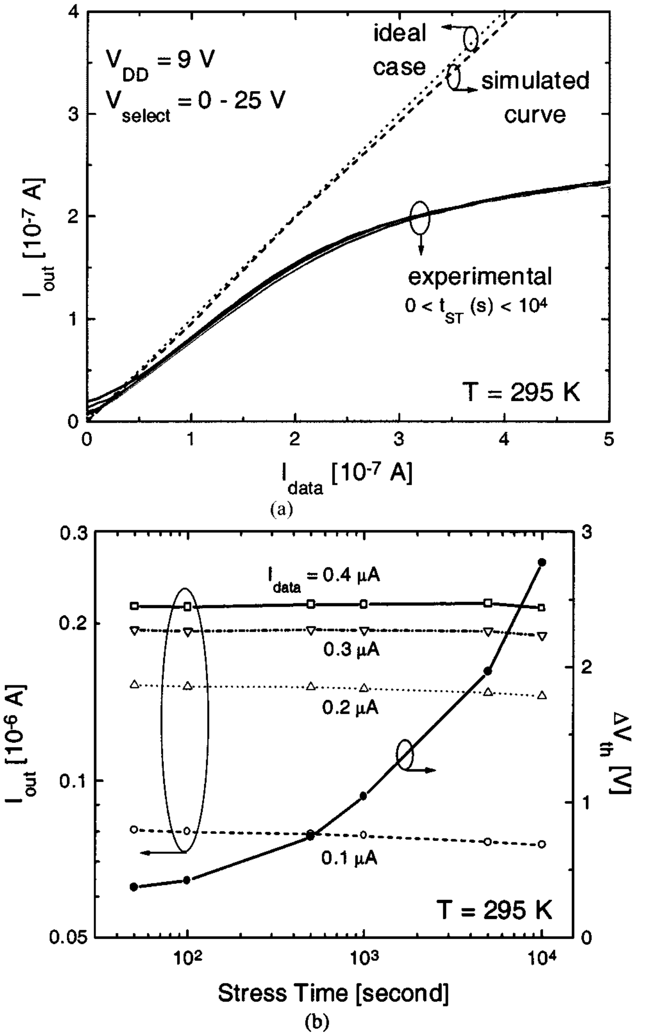

Fig. 2. (a) Output current versus data current characteristics of the four–a–Si:H TF circuit are shown. The dotted line indicates the ideal characteristic. The dashed line represents simulated curve when a separate line in the circuit shown in Fig. 1(a) is used to control V_{dd}. (b) Output current variations as a function of the BTS time at different input data currents are shown. The t_{ST} represents the BTS time. Also shown in the figure is the drive-TFT (T3) threshold voltage shift (ΔV_{th}) with BTS time. ΔV_{th} =final threshold voltage after BTS (V_{th}^{f})-initial threshold voltage (V_{th}^{i}).

because they are not used to control the current output in this circuit.

The above arguments also hold if the OLED current-voltage (*I–V*) characteristic shifts with time, which can happen after a long-term OLED operation. Consequently, the circuit can provide a constant current flow even if local variations of the diode characteristics exist.

The experimental results obtained for this circuit are shown in Fig. 2(a). The data indicate that indeed the output current is flowing even after the input data current is turned OFF, and the pixel electrode is deselected. Thus a continuous excitation can be achieved in this circuit.

To study the influence of the T3 threshold voltage (V_{th}) variation on the circuit performance, we have conducted the bias-temperature stress (BTS) of the drive TFT (T3). After BTS of 20 V on the gate electrode at 295K for about 10^4 s, the output current levels remain essentially unchanged, as shown in Figs. 2 (a) and (b). During the BTS, the V_{th} shifted from 6.4 to 9.2 V (e.g. $\Delta V_{th} = 9.2 - 6.4\ V$ =2.8 V), Fig. 2(b). At the same time, the output current changed only by ~1% at high input current (≥0.5 μA) and by ~5% at low input current (≤0.1 μA). These results indicate that this circuit is able to compensate for the TFT V_{th} variation to ensure a stable, constant output current level. This will allow to achieve both a good control of the display gray levels and a uniform luminance distribution over the whole AM-OLEDs.

In the ideal case $I_{\rm out} = I_{data}$, as shown in Fig. 2(a). However, our experimental data shows that $I_{\rm out}$ is lower than the ideal value, and the deviation becomes larger at higher I_{data}. The curve starts to saturate at ~0.4 μA, resulting in a small $I_{\rm out}$. This behavior is due to the shift of T3 operation point from the saturation to linear region. In this case during the OFF-state, V_{dd} is not high enough to keep T3 in the saturation region of operation. So $I_{\rm out}$ cannot reach the ideal level as it is during the ON-state. A higher V_{dd} is needed to enhance the output current level, but at the same time this will introduce some deviations at low current levels. This deviation can be avoided when a separate line is provided to control T4 gate voltages [8]. Furthermore, the OLED emulating configuration T5-C_{diode} has a parabolic current–voltage characteristic, while the current-voltage curve of real OLED shows an exponential behavior. Consequently, when this circuit is combined with the OLED and a separate T4 gate line, a much higher V_{dd} voltage can be selected to achieve a much higher output current level (≥5 μA) with an acceptable deviation (<0.1%) at low current levels [Fig. 2(a)].

In conclusion, we have developed a constant current-source pixel electrode circuit based on four a–Si:H TFTs. We have shown that this circuit can provide a stable current output independent of TFT threshold voltage shift. This circuit can potentially be used for the AM-OLEDs.

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