70.3: Current-Scaling a-Si:H TFT Pixel Electrode Circuit for AM-OLEDs

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Abstract

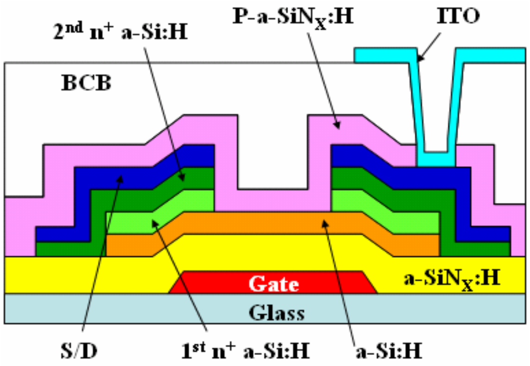
We fabricated and characterized the amorphous silicon thin-film transistor (a-Si:H TFT) pixel electrode circuit with current-scaling function that can be used for active-matrix organic light-emitting displays (AM-OLEDs). As expected from previously reported simulation results, fabricated circuit showed an acceptable current-scaling performance for a high-resolution AM-OLED based on a-Si:H TFTs.

1. Introduction

Over last several years, it was shown by several authors [1-5] that the current driving pixel electrode circuits are among the most desirable solutions for active-matrix organic light-emitting displays (AM-OLEDs). However, as display size and resolution increase, a large timing delay can be observed at a low data current and its importance increases with the display size [6]. To address this issue, several solutions have been proposed based on poly crystalline silicon thin-film transistor (TFT) technology such as current-mirror circuit [7, 8] and series-connected TFT circuit [9]. Besides poly-Si TFTs, we also proposed amorphous silicon TFT (a-Si:H TFT) based current-scaling pixel electrode circuit to address this problem [6, 10]. In this paper, for the first time, we report on the electrical characteristics of the fabricated pixel electrode circuit based on this design, and present its current-scaling function in comparison with the previously published results.

2. Fabrication of Pixel Electrode Circuit

First, chrome layer (Cr, 2000Å) was deposited on glass substrate by a sputtering method, then was patterned by photo-lithography process using wet-etching CR-7 solution (Mask #1) to define gate electrodes. After soaking in GP:H_2O (1:15), acetone, and methanol, the substrate was rinsed in DI water for 10 minutes, and finally blown dry with the N_2 gas. Tri-layer composed of hydrogenated amorphous silicon nitride (a-SiN_X:H, 3000Å) / intrinsic hydrogenated amorphous silicon (a-Si:H, 1500Å) / P-doped a-Si:H layer (n^+ a-Si:H, 200Å) was deposited next in multi-chamber plasma-enhanced chemical-vapor deposition (PECVD) system at 300ºC. A gas mixture of SiH_4 and NH_3, and SiH_4 and H_2 was used for a-SiN_X:H and a-Si:H layer deposition, respectively. First n^+ a-Si:H layer was used to achieve a good ohmic contact to a-Si:H. After definition of the device active island by wet-etching (Mask #2), substrate was dipped in HF solution to remove native oxide before deposition of a second n^+ a-Si:H layer (300Å), which was used to realized an ohmic contact to edges of a-Si:H island. Next, molybdenum / aluminum / molybdenum (Mo/Al/Mo, 1000Å/3000Å/1000Å) multi-layer was deposited by thermal coater, and metal source / drain (S/D) contacts were defined by wet-etching (Mask #3). Acetone supersonic solution was used to remove positive photo-resist. Using S/D metal as a mask, the back-channel-etching was performed by reactive ion etching (RIE) to remove exposed n^+ a-Si:H layer between source and drain contacts. Finally, a-SiN_X:H (3000Å) top passivation layer (P) was deposited by PECVD method followed by spin coating of the benzo-cyclo-butene (BCB) plabarization layer that was cured in a furnace at 250°C in nitrogen ambient. Planarized a-Si:H TFTs by BCB were already reported previously [11, 12]. The pixel electrode indium tin oxide (ITO) was connected to S/D using via formed through the BCB / P-a-SiN_X:H bi-layer by RIE (Mask #4). ITO (1200Å) was deposited by a DC magnetron sputtering at room temperature, and patterned by wet-etching (Mask #5) in a mixture of HCl, HNO_3, and DI water at 60 ºC [13]. Finally, ITO was thermally annealed at 250 ºC in nitrogen.



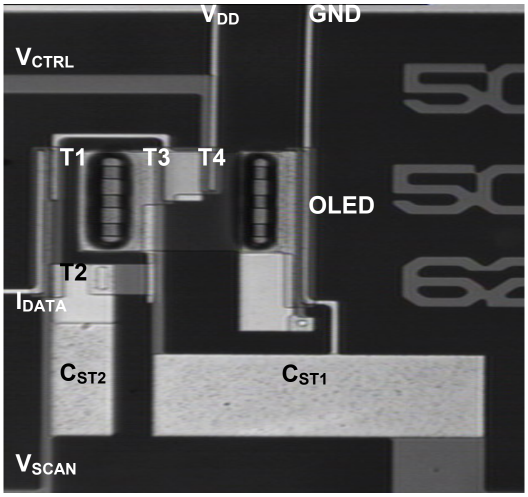


Figure 1 The schematic cross-section and top view of fabricated a-Si:H TFTpixel electrode circuit.

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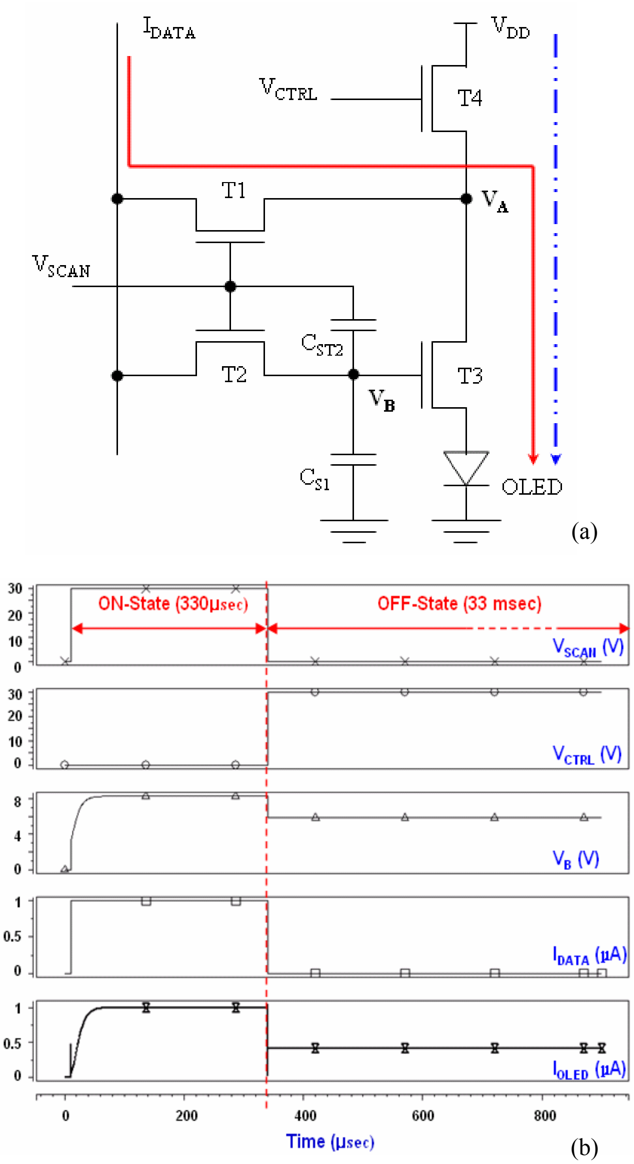

Figure 2 Schematic of (a) the cascaded-capacitor pixel electrode circuit and (b) operational wave forms simulated by HSPICE.

3. Operation and Measurement of Fabricated Current-Scaling Pixel Electrode Circuit

The fabricated current-driven pixel electrode circuit consists of three switching TFTs (T1, T2, and T4), one driving TFT (T3), and two storage capacitors (C_{ST1}, C_{ST2}) connected between a scan line and ground with a cascade structure, Figure 2 (a). Here we define $I_{OLED-ON}$ and $I_{OLED-OFF}$ as the current flowing through OLED during the ON- and OFF-state, respectively. During the ON-state, V_{SCAN} turns on the T1 and T2, and I_{DATA} ($=I_{OLED-ON}$) passes through T1 and T3 to OLED while the T4 remains turned-off by V_{CTRL}, shown as the solid line in Fig 2 (a). When the pixel changes from the ON- to OFF-state, V_{SCAN} turns off T1 and T2, and V_{CTRL} simultaneously turns on T4. Since gate bias of T3 (V_{B_ON}) is reduced to V_{B_OFF} by the ratio of cascaded capacitor ($V_{B\_OFF} = V_{B\_ON} - \Delta V_{SCAN} \cdot C_{ST2} / (C_{ST1}+C_{ST2})$), a scaled-down data current (I_{OLED_OFF}) will flow through OLED, shown as the dashed line in Fig 2 (a). More details about this circuit operation can be found in [6].

To analyze the electrical performance of the pixel circuit, we measured $I_{OLED-ON}$ and $I_{OLED-OFF}$ flowing through the diode (OLED is represented here by a-Si:H TFT with gate and drain connected together) by applying I_{DATA}, V_{CTRL}, and V_{SCAN} as shown in Fig. 2 (b). At the same time, constant DC V_{DD} and ground (GND) were applied. All measurements were done at room temperature, and all signals were applied using HP8110A function generator through a probe station. The time for ON- and OFF-state was set to 0.33 and 33ms, respectively. During ON-state, V_{SCAN} and V_{CTRL} were held at 30 and 0V, respectively while I_{DATA} was swept from 0.2 to 10 μA for each measurement. During OFF-state, V_{SCAN} and V_{CTRL} were changed to 0 and 30V, respectively while I_{OLED} was measured with V_{DD} set at 30V. It should be noted that the I_{DATA} must be turned off when the circuit operation changes from ON- to OFF-state. Otherwise, the V_{DATA} measured when I_{DATA} is supplied will increase to high value (>40V) to keep the current flowing when T1 and T2 are turned off, since the probe of I_{DATA} is set to the current supply mode. This high V_{DATA} can result in a large T2 leakage current, which increase the voltage at node B (V_{B_OFF}). Accordingly, the I_{OLED_OFF} will also increase since V_{B_OFF} increases.

Therefore, for proper circuit operation, I_{DATA} should be turned-off during OFF-state as shown in Fig. 2 (b). However, even though the I_{DATA} was turned off, the measured I_{OLED_OFF} decreased slightly during OFF-state due to T2 current leakage, which originated from the voltage difference between source and drain. This current leakage causes the V_{B_OFF} to decrease. To reduce the variation of V_{B_OFF}, the following steps were taken: (i) the value of V_{DATA} during ON-state was measured while supplying DC I_{DATA}. Since the resistance of T1 was very small during ON-state, the voltage at node B (V_{B_ON}) was expected to be the same as measured V_{DATA}. (ii) Then, V_{DATA} obtained in step (i) was applied instead of I_{DATA} on the data line during ON-state. Since the V_{DATA} was same as V_{B_ON} and it would supply the same current as I_{DATA}, the voltage levels during OFF-state between source and drain of T2 could be very similar so that the T2 leakage current was negligible and I_{OLED} was stable during OFF-state.

4. Electrical Properties of Current-Scaling Pixel Electrode Circuit

To investigate the current scaling ratio of the fabricated pixel electrode circuit, we changed the I_{DATA} from 0.2 to 10μA and measured the corresponding I_{OLED_ON} and I_{OLED_OFF} flowing through the diode for different ratios of cascaded-capacitors. In ON-state, the I_{OLED_ON} is identical to the data current (I_{DATA}) since the external driver directly controls the OLED current, Fig. 3 (a). When the pixel circuit operates in OFF-state, the diode current (I_{OLED_OFF}) is scaled-down by the ratio of cascade capacitor as discussed above and in [10]. From Fig. 3 (b), it is obvious that the larger C_{ST2}/C_{ST1} results in significant decrease of the I_{OLED_OFF} at lower I_{DATA}. However, as shown previously [10], too large ratio of C_{ST2}/C_{ST1} (> 1/3) resulted in the saturation of I_{OLED_OFF}, which deteriorate the current scaling function eventually.

Since the OLED current value is different during ON- and OFF-state, we define the average OLED current (I_{AVE}) during one

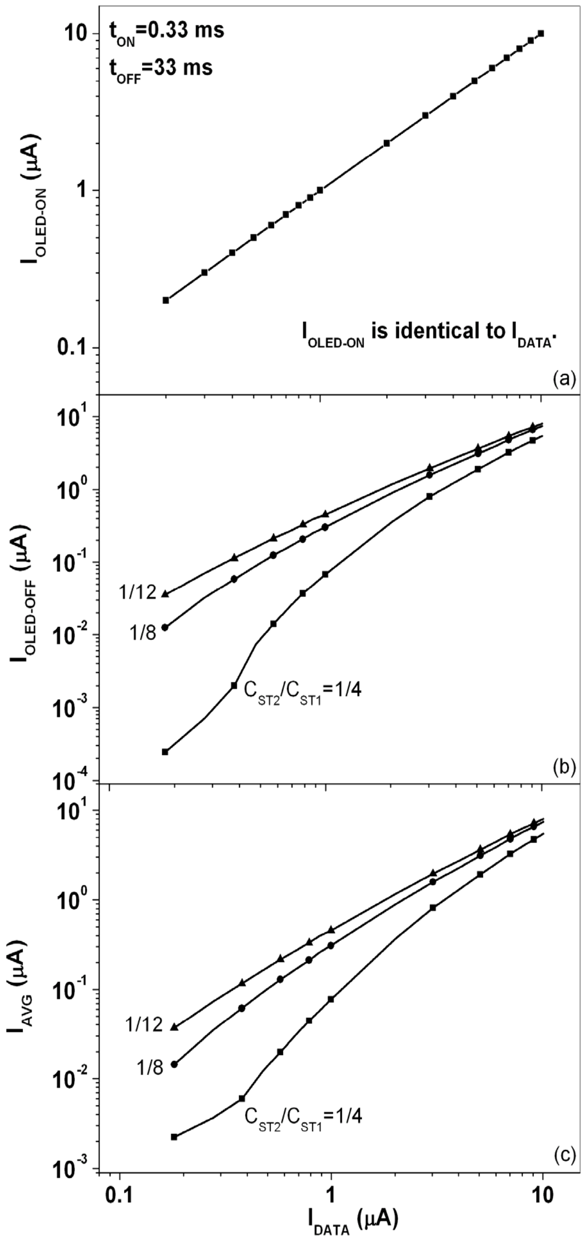

Figure 3 Variation of the measured I_{OLED_ON}, I_{OLED_OFF} and I_{AVE} as a function of I_{DATA} (=I_{OLED_ON}) for various C_{ST2}/C_{ST1} ratios.

frame time [10] as I_{AVE}= ($I_{OLED\_ON} \cdot t_{ON}$ + $I_{OLED\_OFF} \cdot t_{OFF}$) / ($t_{ON}$ + t_{OFF}), where t_{ON} and t_{OFF} is the ON- and OFF- period during the frame time, respectively. The variation of I_{AVE} versus I_{DATA} in one frame period (t_{ON} + t_{OFF}) for different C_{ST2}/C_{ST1} ratios is shown in Fig. 3 (c). Since the OFF-state period is much longer than ON-state, though I_{OLED_OFF} is very small during OFF-state, it can reduce the I_{AVE} even if the I_{OLED_ON} (=I_{DATA}) is large. For example, the fabricated pixel electrode circuit can generate I_{AVE} ranging from 2 nA to 5 μA while I_{DATA} swept from 0.2 to 10 μA. Therefore, during one frame time, we can achieve very wide range of OLED current levels by supplying high data current levels.

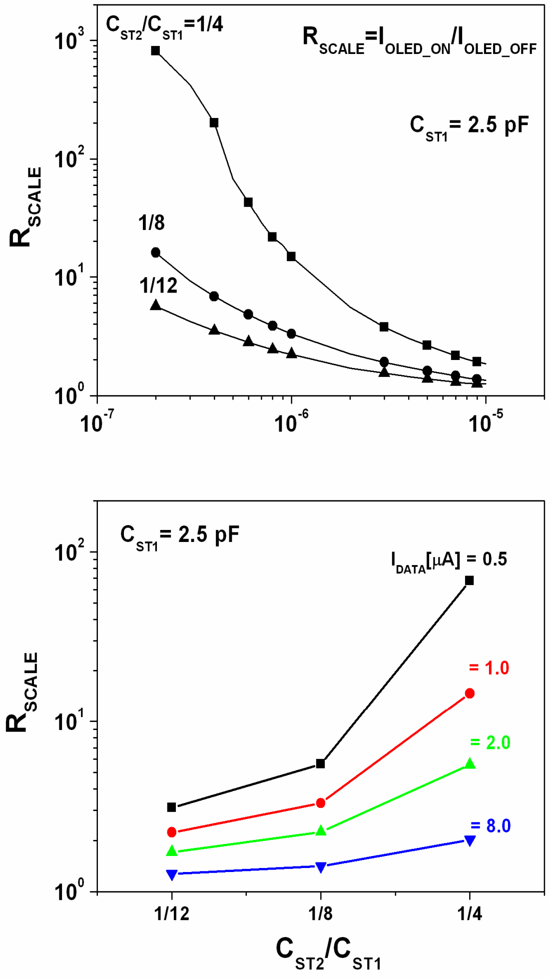

Figure 4 Variation of the measured current scaling ratio as a function of (a) I_{DATA} and (b) ratio of storage capacitances for fabricated cascaded-capacitor pixel circuit.

The evolution of the scaling ratio (R_{SCALE}= $I_{OLED\text{-}ON}/I_{OLED\text{-}OFF}$) for different ratios of C_{ST2}/C_{ST1} as a function of I_{DATA} is shown in Fig. 4 (a). In this figure, we can see that for C_{ST2}/C_{ST1}=1/4, R_{SCALE} decreases from 816 to 1.9 as I_{DATA} increases from 0.2 to 10μA, and an ideal non-linearity of R_{SCALE} can be achieved; e.g. a very high R_{SCALE} at low I_{DATA} levels (low gray scales) and a low R_{SCALE} at high I_{DATA} levels (high gray scales) can be produced. The variation of R_{SCALE} with the C_{ST2}/C_{ST1} is also shown in Fig. 4 (b). The measured results show that for fixed I_{DATA}, R_{SCALE} increases as C_{ST2} increase from 210 to 625 fF, corresponding to an increase of C_{ST2}/C_{ST1} from 1/12 to 1/4. For constant C_{ST2}/C_{ST1}, R_{SCALE} increases as I_{DATA} decreases as shown in Fig. 4 (a). Therefore, for a fixed ratio of C_{ST2}/C_{ST1} determined from the pixel electrode circuit design, we can expect the certain output OLED current range. These experimental results are comparable to simulated results previously reported [10].

5. Comparison with Other Pixel Electrode Circuits

To demonstrate the current-scaling function of the pixel electrode circuit in comparison with both the conventional current-driven [4] and current-mirror pixel circuits [7], we fabricated all three pixel electrode circuits using the same a-Si:H TFT technology, and measured I_{AVE} as a function of I_{DATA} for each pixel electrode circuit as shown in Fig. 5. Since I_{OLED_ON} for all three circuits was identical to I_{DATA}, the current-driven circuit did not show any current-scaling function. On the contrary, while the current-mirror circuit showed only a fixed current-scaling by the ratio of T4/ T3 over all I_{DATA} range, the proposed cascaded-capacitor pixel circuit showed non-linear current-scaling function for variable current-scaling ratio depending on I_{DATA}. When I_{DATA} varies from 2×10^{-7} A to 10^{-5} A, the proposed cascaded-capacitor pixel circuit with the ratio of $C_{ST2}/C_{ST1}=1/4$ can provide I_{AVE} ranging from 2×10^{-9} A to 5.4×10^{-6} A. Hence much wider range I_{AVE} levels can be achieved by this circuit in comparison with the conventional current-driven pixel circuit (2×10^{-7} to 10^{-5} A) and the current-mirror pixel circuit (10^{-8} to 2×10^{-6} A).

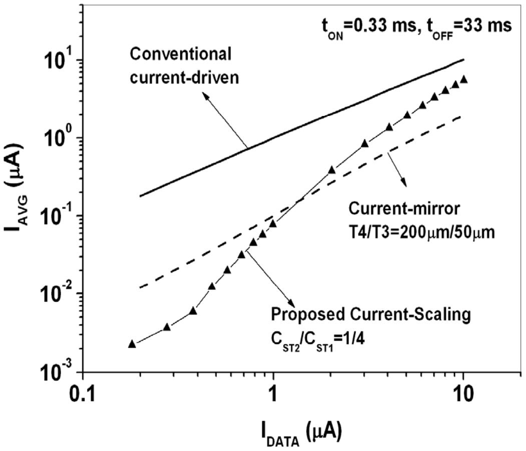

Figure 5 Comparison of I_{AVE} versus I_{DATA} for among conventional current-driven, current-mirror, and proposed pixel circuits.

6. Conclusion

When a low I_{DATA} is used to express a low gray scale, the conventional current-driven pixel circuit has a problem of slow programming time. On the contrary, when a high I_{DATA} is used to express a high gray scale, the current-mirror circuit has a problem of high power consumption due to a fixed current-scaling ratio. In the proposed circuit, by using cascaded-capacitors connected to the driving TFT, we could produce non-linear scaling-function that has a high scaling ratio at low current levels and a low scaling ratio at high current levels. Therefore, using this pixel circuit, we expect to avoid the unnecessary power consumption at high current levels and minimize the programming time at low current levels, which are supposed to be ideal characteristics for a high-resolution AM-OLED based on a-Si:H TFTs.

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8. References

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