# Amorphous Silicon Thin-Film Transistors Based Active-Matrix Organic Light-Emitting Displays

**J. Kanicki, J.-H. Kim, J.Y. Nahm, Y. He, and R. Hattori***

Organic & Molecular Electronics Laboratory, Department of EECS,
The University of Michigan, Ann Arbor, MI 48109, USA.
*Department of Electronic Device Engineering, Kyushu University, Fukuoka, Japan

## ABSTRACT

In our laboratory we have simulated, designed, and fabricated hydrogenated amorphous silicon (a-Si:H) thin-film transistors (TFTs) based pixel electrode circuits for active-matrix organic light-emitting displays (AM-OLEDs). These pixel circuits, having very small feed-through voltages, can supply a continuous output current at an adequate level for AM-OLEDs up to 500 dpi of resolution. Each pixel electrode has also compensation circuits that will allow to adjust the output current level for the OLED and a-Si:H TFTs threshold voltage variations. Therefore, we can control display brightness uniformity at an acceptable level.

## INTRODUCTION

In the past several years different types of pixel electrode circuits have been proposed for the active-matrix (AM) organic light-emitting displays (OLEDs). For the micro-displays, crystalline silicon (c-Si) CMOS based pixel electrode circuits have been developed [1-3]. These c-Si based AM-OLEDs have limited size (< 2 inch) and use organic light-emitting devices with the top transparent cathode metal electrode. For large-area AM-OLED, the polycrystalline silicon (poly-Si) thin film transistor (TFT) pixel electrode circuits have been introduced [4-7]. The advantage of poly-Si TFT AM-OLEDs is that the display drivers can be integrated with the pixel electrode circuits. Another possible technology for AM-OLED is hydrogenated amorphous silicon (a-Si:H) TFT technology. This type of technology can be very cost effective over large-area.

Important issue that needs to be addressed in the AM-OLEDs is a poor uniformity of display brightness that can be caused by TFT and/or OLED electrical degradation. This problem cannot be easily addressed if a simple voltage driving method is used to produce display gray levels. A few different methods have been proposed to address this problem, such as current driving [7-10], time-ratio gray-scale [6], and area-ratio gray-scale methods [5].

In this paper, we will summarize circuit simulation and experimental results obtained for the a-Si:H three and four TFTs AM-OLEDs pixel electrode circuits developed in our group that can overcome the brightness uniformity problem.

## A-SI:H TFT PIXEL ELECTRODE CIRCUITS

In AM-OLED, in order to turn on OLED continuously, a minimum of two a-S:H or poly-Si TFTs are needed. It should be noticed that, in this type of pixel electrode circuit, any variation of TFTs and OLEDs electrical parameters will introduce different output current levels for each pixel even if driving TFT gate-source voltage and drain-source voltage are kept constant. This output current non-uniformity will result in OLED brightness non-uniformity since luminance of the OLED is usually proportional to applied current level.

To overcome this problem, we proposed two different pixel electrode circuits configurations: voltage driving 3-a-Si:H TFTs and current driving 4-a-Si:H TFTs circuits. Both configurations have their own strengths and shortcomings.

### *3-a-Si:H TFTs pixel electrode circuits*

The 3 – a-Si:H TFT pixel electrode circuit is shown in *Figure 1* [11]. In this schematic diagram, $C_{ST}$ is storage capacitor, T1 is switching TFT, T2 is active resistor, and T3 is large-sized high-capacity constant current driving TFT.

The pixel electrode circuit operation of the AM-OLED can be explained as follows. During the gate scan voltage ($V_{select}$) pulses to a high level, an image data ($V_{data}$) is fed to the gate electrode of the constant current driving TFT controlling the amount of the drain current (driving current) of the driving TFT. The drain electrode of the driving TFT is connected to a high-voltage source through the active resistor. At the same time, $V_{data}$ is stored in the storage capacitor. For a given frame time depending on the refresh rate of the AM-OLED design, the gate voltage of the constant current driving TFT remains at the same level even after $V_{scan}$ drops low, since $C_{ST}$ keeps the image data ($V_{data}$). In this case, the current compensation circuit is represented by an active resistor (T2) TFT, with gate and drain electrodes connected together, operating only in saturation mode. The operating current determines the voltage drop across the active resistor. For any reason, e.g., when the threshold voltage of the constant current driver increases or the turn-on voltage of the OLED increases, if the current flowing through the active resistor decreases, the voltage drop across the active resistor decreases. That will allow for a high current to flow back through the OLED pixel, compensating for the parameter changes in both the constant current driver and the OLED.

The pixel electrode circuit performance of the AM-OLED was simulated using the Cadence circuit simulator, Spectre. The a-Si:H TFT model used in this simulation was previously developed within our group [12]. Using the OLED and a-Si:H TFT models, 100 x 100 active-matrix array for AM-OLED with 300 dpi resolution (127 μm x 127 μm pixel size) was designed and simulated for driving voltages ($V_{drv}$) ranging from 4 to 10 V. In each case, the data and the scan voltages were the same as the driving voltages. The transient pixel electrode circuit simulation results are shown for 30 msec. The ON- and OFF-states are shown for the driving voltage of 10 V, *Figure 2.* The storage capacitance was optimized during the AM-OLED simulation. The optimum value was chosen to be large enough for good image retention and to fit into the pixel area (e.g., pixel electrode aperture ratio was optimized in this design).

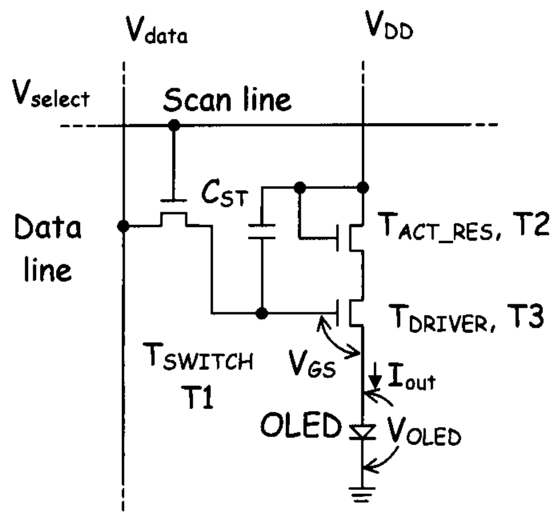


Figure 1. A schematic diagram of the AM-OLED pixel electrode circuit [11].

With a storage capacitance of 0.4 pF, the switching between the ON- and OFF-states was completed within the scan time. In addition, the image data stored in the storage capacitor was retained without any loss during the retention period for AM-OLED frame time (60 Hz).

During the AM-OLED pixels operation, the feed-through voltage drops occur while the $V_{scan}$ signal drop. Feed-through voltage is an abrupt voltage change induced by a capacitive coupling of the gate signal through the gate-source capacitance. Typically, the AM-LCD pixel electrode circuit has a feed-through voltage of about 1 to 2 V at the source electrode of the switching TFT [11, 13]. On the other hand, the feed-through voltage of our AM-OLED pixel is only of a few tenth of mV. This was achieved by using the cascaded TFT connection of the switching TFT and the constant current driving TFT. This low feed-through voltage will enhance the gray level controllability of the AM-OLED. Another advantage of the gray level control in AM-OLED over AM-LCD is the absence of the asymmetrical feed-through voltage effect associated with the dual data voltage levels ($V_d$+ and $V_d$-).

The extensive pixel electrode circuit simulation and analysis results indicate that a continuous pixel electrode excitation can be achieved with these circuits, and a pixel electrode driving output current level up to 1.4 μA can be reached with the a-Si:H TFT technology.

AM-OLEDs with the resolution up to 500 dpi have been designed with 3-a-Si:H TFTs configuration in our group. The AM-OLED described in this paper features 45 % aperture ratio, 300 dpi pixel, switching TFT (with W/L of 30 μm /10 μm), active resistor TFT (with W/L of 15 μm / 10 μm), driving TFT (with W/L of 105 μm / 10 μm), and $C_{ST}$ of 0.4 pF.

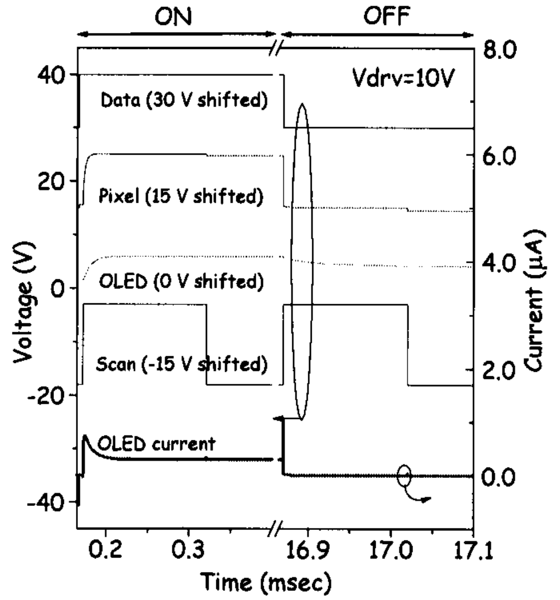


Figure 2. Simulation example of the AM-OLED operation for driving voltages of 10 V.

***4-a-Si:H TFTs pixel electrode circuits***

Four a-Si:H TFT current driving pixel electrode circuit [14-17] is shown in *Figure 3.* T1 and T2 serve as switches to adjust OLED output current ($I_{out}$) to input data current ($I_{data}$) level when a pixel electrode is selected ($V_{select1}$ is high, $V_{select2}$ is low). T4 is another switching TFT that is turned on only when the pixel electrode is deselected ($V_{select1}$ is low, $V_{select2}$ is high). A common source line ($V_{dd}$) is used to supply $I_{out}$ current when the pixel electrode is deselected.

T3 operates as driving TFT connected to OLED. During pixel-selected period, $I_{out}$ value is set to match $I_{data}$ as $I_{data}$ flows from input current source through data busline-to-T2-to-T3. During the same pixel electrode selected period, gate-source ($V_{gs}$=$V_{Cst}$) and drain-source ($V_{ds}$) voltage values are set to certain values to achieve $I_{out}$=$I_{data}$ with the help of charges stored in storage capacitance ($C_{ST}$) by T3. These $V_{gs}$ and $V_{ds}$ can vary from pixel-to-pixel to maintain $I_{data}$=$I_{out}$ independent of the OLED and TFTs operating parameters. Examples of the device parameter variations are OLED and TFT threshold voltages, and TFT mobility, which could result from manufacturing and material variations, and pixel electrode circuitry aging.

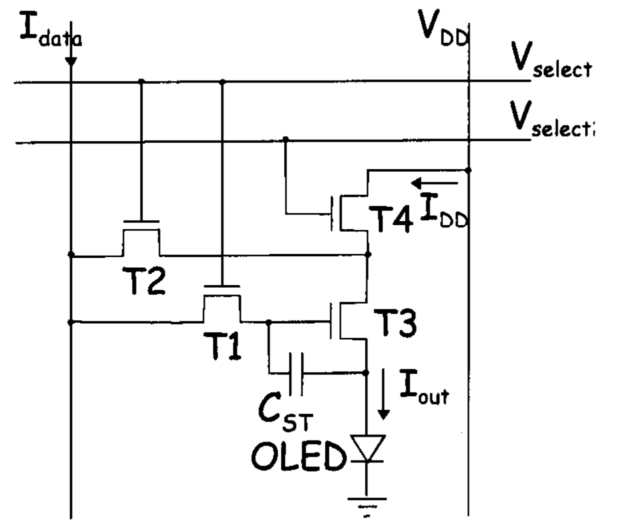


Figure 3. The a-Si:H four TFTs current driving pixel electrode circuit.

During pixel-deselected period, $I_{out}$ flows through $V_{dd}$ line–T4–T3, and should be maintained very closely to the value set during pixel-selected period. This is possible because the drain current of TFT does not change significantly for the same $V_{gs}$ and different $V_{ds}$ values in TFT saturation region. However, for a-Si:H TFTs with non-ideal saturation characteristics, as the $V_{ds}$ of T3 increases during pixel-deselected period, $I_{out}$ could be higher than initial $I_{data}$. Another effect that can change $I_{out}$ during the transition from pixel-selected to pixel-deselected period is charge redistribution of $C_{ST}$ due to TFT parasitic capacitances of T1, which results in $V_{Cst}$ and $I_{out}$ reduction during pixel-deselected period.

Simulation and experimental results have confirmed that $I_{out}$ can be auto-corrected for OLED and TFT characteristic variation when four TFTs pixel electrode circuit is used, *Figure 4* [14-17]. This compensation cannot be achieved for two TFTs pixel electrode circuits. An example showing simulated $I_{out}$ current dependence on driving TFT threshold voltage shifts for two- and four TFT pixel electrode circuits is shown in *Figure 5*. The output current is simulated for pixel-deselected period (one frame time).

For this simulation Cadence SPECTRE software was used, and OLED and a-Si:H TFT models were fitted to experimental data developed in our group [12]. In our simulation, the following parameters were used: TFT mobility ($\mu$)=0.49 $cm^2/Vs$ in linear region, TFT threshold voltage ($V_{th}$) = 2.55V, W/L(T1) = 50μm/6μm, W/L(T2) = 100μm/6μm, W/L(T3) = 172μm/6μm, W/L(T4) = 189μm/6μm, $I_{data}$ = 5μA, $V_{select1}$(high) = $V_{select2}$(high) = 30V, $V_{select1}$(low) = $V_{select2}$(low) = 0V, $V_{DD}$ = 30V, $C_{ST}$ = 5pF, $C_{oled}$ = 1.5pF, TFT parasitic capacitance model parameter: $C_{gso}$ (gate-to-source) = $C_{dso}$ (gate-to-draion) = $50\times10^{-10}$F/m.

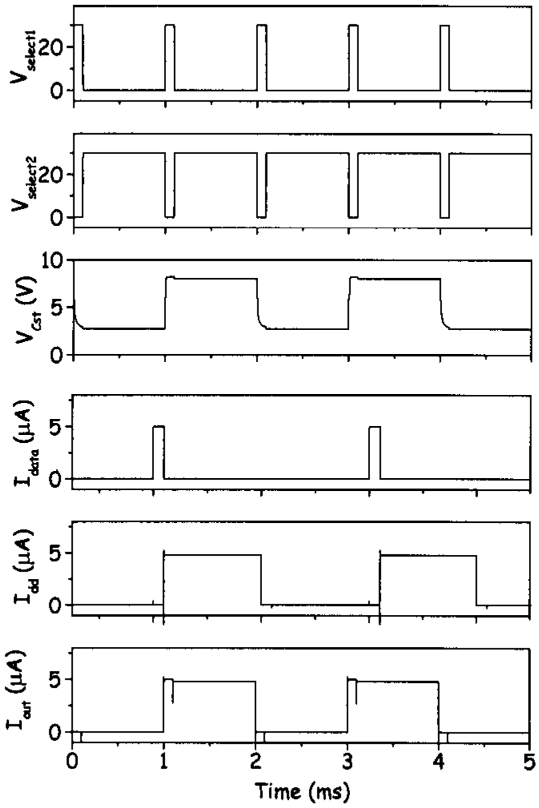


Figure 4. Simulation example of pulse diagram for 4-a-Si:H TFTs current driving pixel electrode circuit for $I_{data}$ = 5μA.

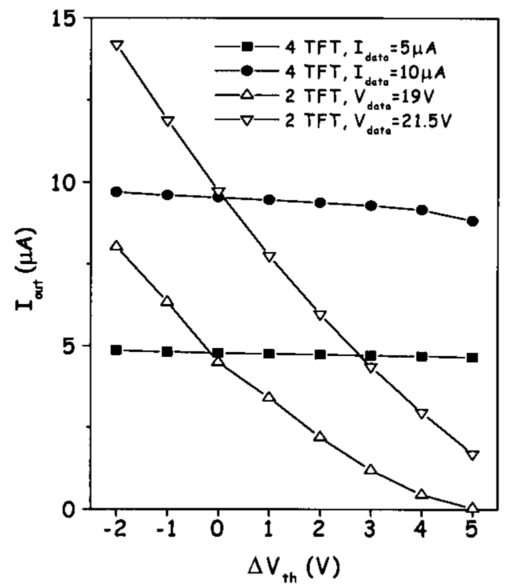


Figure 5. Simulation results of the OLED output current ($I_{out}$) dependence on TFT threshold voltage shifts for two TFTs voltage and four TFT current driving pixel electrode circuits.

For the two TFTs voltage driving pixel electrode circuit, $V_{gs}$=~8.1V is needed to achieve Iout=5μA when $V_{th}$=2.6V and threshold voltage shift is zero ($\Delta V_{th}$=0V). As expected, for the two TFTs pixel electrode circuit, $I_{out}$ decreases as ΔVth increases since TFT output current is proportional to $(Vgs - Vth)^2$ in saturation region. It is obvious when ΔVth=5.5V and Vgs-$V_{th}$=~0V, $I_{out}$ is close to zero. In the four TFT current driving pixel electrode circuit, $V_{gs}$ is automatically set to a certain value to produce $I_{data}$=5μm regardless of Vth shifts and $I_{out}$ does not decrease much even up to $\Delta V_{th}$=10V. The reduction of $I_{out}$ observed for the four TFTs pixel electrode circuit is due to reduction of $V_{ds}$ of T3 since $V_{ds}$ of T4 is high for higher $V_{th}$. Overall, this result clearly indicated that four TFT current driving pixel electrode circuit has much lower reduction of $I_{out}$ over two TFTs pixel electrode circuit.

In the ideal case, $I_{out}$ should be equal to the $I_{data}$. But in reality $I_{out}$ is limited by a-Si:H TFT characteristics and driving voltage conditions. The simulated results shown in *Figure 6* indicate that $I_{out}$ is slightly lower than the ideal value when $I_{data}$>~20μA and the deviation increases with increasing $I_{data}$. The discrepancy between $I_{data}$ and $I_{out}$ is due to shift of the T3 operation point from the saturation into the linear region. During the pixel-deselected period, if $I_{data}$ is high, the $V_{ds}$ shifts to lower value that is limited by $V_{dd}$ value. Thus, T3 operates in the linear region instead of the desired saturation region and $I_{out}$ cannot keep the same current level at pixel-selected period. However, according to our calculation, $I_{out}$ current level over 20 μA is not necessary for AM-OLED. Using simple calculations and pixel electrode circuit simulations, we have designed AM-OLED based on 4-a-Si:H TFTs pixel electrode circuit.

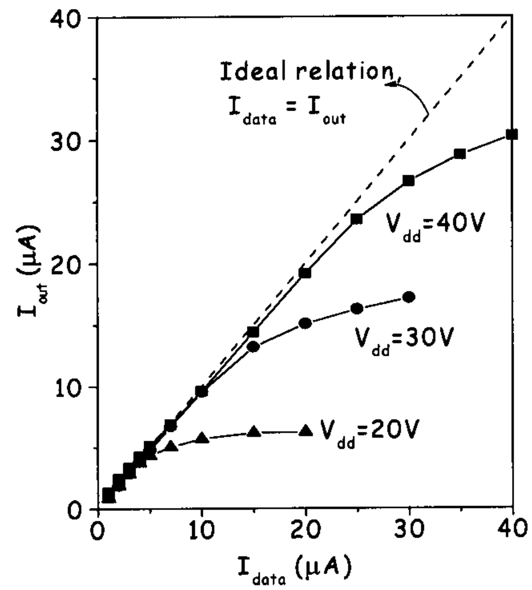


Figure 6. Relation between OLED output current ($I_{out}$) and input data current ($I_{data}$) when $V_{select1}$ (high) = $V_{select2}$ (high) = $V_{dd}$ = 20, 30, and 40V, respectively.

An example of such AM-OLED is shown in *Figure 7*. So far, the AM-OLEDs with 4-a-Si:H TFT pixel electrode circuits having the resolution up to 300 dpi have been developed in our group.

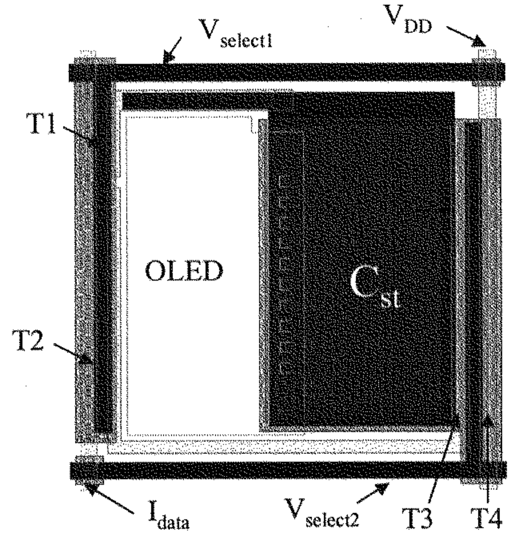


Figure 7. Top view and cross-section of the pixel electrode with pixel size=254×254μm$^2$, OLED size=77×185μm$^2$, aperture ratio=22%, and $C_{ST}$=3.5pF.

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**REFERENCES**

1. K. Pichler et al., *Proc. of SPIE*, 3797, 258 (1999).
2. T. Feng et al., *Proc. of SPIE*, 4105, 30 (2001).
3. H.E. Abraham et al., *Proc. of SPIE*, 4105, 37 (2001).
4. R.M.A. Dawson et al., *Proc. of SID Sym.*, p. 11 (1998).
5. M. Kimura et al., *IEEE Trans. on Elec. Dev.*, 46, 2282 (1999).
6. T. Shimoda et al., *Proc. of IEDM*, p. 107 (1999).
7. M. Mizukami et al., *Proc. of SID Sym.*, p. 912 (2000).
8. K. Inukai et al., *Proc. of SID Sym.*, p. 924 (2000).
9. G. Rajeswaran et al., *Proc. of SID Sym.*, p. 974 (2000).
10. S.J. Bae et al, *Proc. of IDRC Sym.*, p. 358 (2000).
11. J.-H. Kim et al., *Proc. SPIE Medical Imaging*, 4319, 306 (2001).
12. C.-Y. Chen et al. *Proc. of ESSDERC'96*, p. 1023 (1996).
13. M. Ohta, M. et al., *Japan Display*, 431 (1992)
14. R. Hattori et al., *IEICE Trans. Electron.*, E83-C, 779 (2000).
15. Yi He et al., *IEEE EDL*, 21, 590 (2000).
16. Yi He et al., *Jpn. J. Appl. Phys.*, 40, 1199 (2001).
17. Yi He et al., *IEEE Trans. on Elec. Dev.*, 48, 1322 (2001).