

4.2: TFT AMOLED Pixel Circuits and Driving Methods

James L. Sanford and Frank R. Libsch

T. J. Watson Research Center, IBM, Yorktown Heights, New York

Abstract

Active matrix organic light emitting diode (AMOLED) displays are now entering the market place. TFT active matrix allow OLED displays to be larger in size, higher in resolution and lower in power dissipation than is possible using a passive matrix. A number of TFT active matrix pixel circuits have been developed for luminance control while correcting for TFT parameter variations. The circuits and driving methods are reviewed. A new driving method is presented

1. Introduction

The high brightness and efficiencies of organic light emitting diodes (OLEDs) have created considerable interest for displays. Initial OLED display products were first commercialized incorporating passive matrix addressing². While passive matrix addressing simplifies the display fabrication, the number of rows are limited to few hundred. Since the OLED is on only while being addressed, high peak currents are required to obtain average brightness levels. Row line resistance, column line resistance, OLED resistance, OLED capacitance and OLED off current restrict display luminance, size, and format and reduces efficiency^{3,4}.

Incorporating thin film transistors (TFTs), active matrix addressing is used to make large size and high resolution liquid crystal displays (LCDs). The impedance of the liquid crystal materials used is that of a capacitor that varies with applied voltage as the refractive index changes. Applied LC voltages alternate from frame to frame to avoid image sticking due to ion plating. The pixel circuit consists simply of a single transistor and storage capacitor. The data voltages and row signals allow alternating TFT terminal voltages that tend to stabilize transistor characteristics such as threshold voltage.

OLEDs are somewhat difficult to drive uniformly with active matrix TFTs. The most important reasons are: (1) luminance is current, not voltage, dependent, (2) OLED capacitance is very high, (3) TFT dimensions are relatively large, (4) effective TFT gate to drain capacitance (C_{gd}) and gate to source capacitance (C_{gs}) are high and (5) TFT threshold voltages and mobilities may vary from one device to another. The drive TFT must provide current for an OLED to light up. The large TFT dimensions tend to limit transconductance such that OLED is driven a large percentage of a frame time. The large TFT dimensions also limit the number of TFTs that can fit in the available pixel area. Low temperature polysilicon (p-Si) has an advantage over amorphous silicon (a-Si) since mobility can be one to two orders of magnitude higher. Polysilicon transistor widths can be smaller. In addition, the terminal voltages can be lower giving more power efficient operation. The OLED capacitance is so large that the OLED current and voltage can't be driven in to equilibrium in a row time. This coupled with the large TFT terminal gate to source and drain capacitance may result in luminance that depends upon the previous OLED state. Variations in threshold voltage and

mobility depending upon implementation may add to luminance variations. With p-Si, initial variations are higher due to grain size and boundary variations. With a-Si, time related electrical stress can give large threshold voltage variations. AC terminal voltages are useful in minimizing time related electrical stress variations.

An important distinction between different pixel circuits is whether the data being written to the pixel is current or voltage. Another distinction is whether the driving method or the circuit attempts to correct for drive transistor variations. The different circuits and driving methods are reviewed. A new driving method is presented.

2. Simple Pixel Circuits

Two relatively simple pixel circuits, a voltage follower and a current source, are shown in figure 1. In figure 1a, data voltage is written onto the data storage capacitor, C, by T1 when the gate line is brought high. Transistor T3 operates as a voltage or source follower to provide OLED current. T3's drain to source current, I , is proportional to $(V_{data} - V_{oled} - V_t)^2$ for $V_{data} < V_{dd} + V_t$ where V_t is the TFT threshold voltage. It is desirable for OLED driving transistor to operate in saturation so as to minimize current dependence on drain to source voltage. A drawback of this circuit is that the current depends upon the OLED voltage. The OLED voltage may vary from pixel to pixel and increase slowly with usage, ~ 0.1 - 1 mV/hour, providing additional sources of non uniformity.

The OLED voltage dependence on current is eliminated with the circuit shown in figure 1b. T3 is a pft device connected in a common source arrangement. T3 operates as a current source. The current is proportional to $(V_{dd} - V_{data} - V_t)^2$ for $V_{data} > V_{oled} - V_t$.

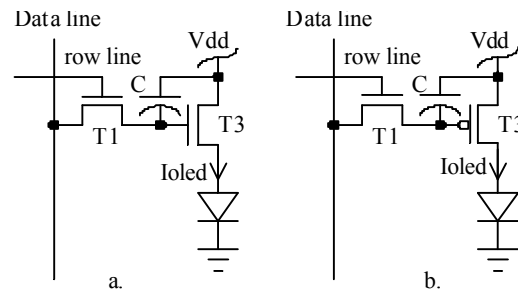


Figure 1. Simple AMOLED pixel circuits.

In both circuits, turning T1 off will increase the voltage across C due to T1's gate to source capacitance. This is a systematic effect that can be corrected with the applied data voltages. As the OLED luminance is changed from one frame to the next, the OLED voltage will change, which modifies the voltage across C due to T3's C_{gs} coupling in figure 1a and T3's C_{gd} coupling in figure 1b. Several addressing frames may be needed for stabilize the luminance.

An issue with both circuits is the current dependence upon the threshold voltage. With p-Si and a-Si, threshold variations can significantly impact the pixel to pixel uniformity. One exception may be the circuit in figure 1b that has been driven hard enough for T3 to operate as a switch. For gray level operation, multiple sub frame addressing is required⁵.

3. Current Data Pixel Circuits

Since the OLED luminance is proportional to current, it is logical to consider current data pixel circuits. Sony is using a p-Si current mirror pixel circuit⁶. An equivalent circuit diagram is shown in figure 2. To set the OLED current, the row line input is brought high while pulling or sinking the data current out of the data line. T1 and T2 are turned on by the row line. Transistor T1 operates as a data switch allowing current to flow from the pixel circuit into the data line. T2 functions as a switch changing operation of T3 to that of a diode, which allows adjustment of the capacitor voltage for matching T3's drain to source current to I_{data} . T4 drives the OLED based upon the capacitor voltage. T4 isolates the OLED from the data writing process. The width of T3 is larger than the width of T4. This allows the data current to be larger in order to set the pixel current within a row time for low luminance levels.

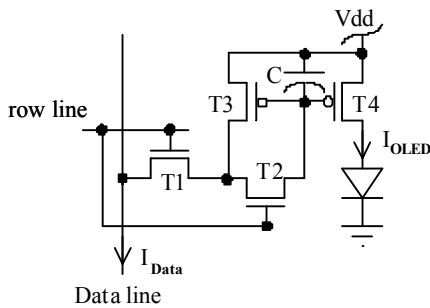


Figure 2. Current mirror circuit incorporating data current

While the threshold voltage of T3 has been compensated by writing method, T4's threshold voltage may differ from T3's at time of fabrication or with usage due to different electrical stress.

Other current writing circuits have been proposed that directly set the current in the OLED driving transistor^{7,8,9}. Equivalent circuit diagrams are shown in figures 3 and 4 incorporating p-Si and a-Si TFT, respectively. These circuits directly compensate for threshold voltage and transconductance variations in the drive transistor. The driving method and device functionality are similar to current mirror. However, the T3 instead of T4 drives the OLED. T4 operates as an off switch for isolating the OLED or the power while writing data. In figure 3a, the data line supplies current data to the pixel circuit. T4 isolates the power supply line. In figure 3b, the data line sinks current out of the pixel circuit while T4 isolates the OLED. The choice of n and p type devices used allows the SW input to be connected to the row line. By using the SW input on the gate of T4 in figures 3 and 4, it is possible to use high data line currents for fast writing. The SW input would need to be modulated by a suitable duty factor.

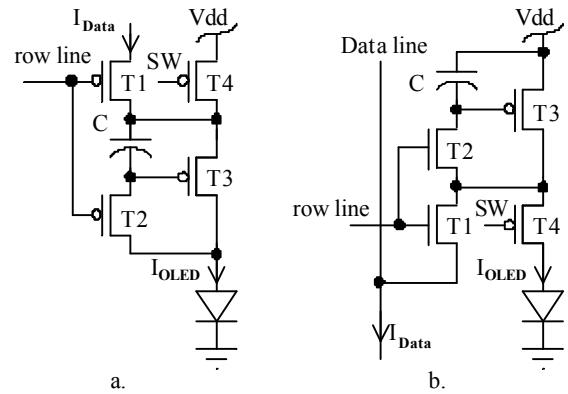


Figure 3. p-Si current data pixel circuit.

Figure 4 shows an a-Si pixel circuit using only nfets. Display fabrication is simplified if the pixel circuit drives the anode rather than the cathode. Since the drain and source current are identical, it is only a matter of perspective for using nfets to form current sources. The SW input can be eliminated by connecting it to Vdd. This allows T4 to function like a diode and still provide some power supply isolation when writing.

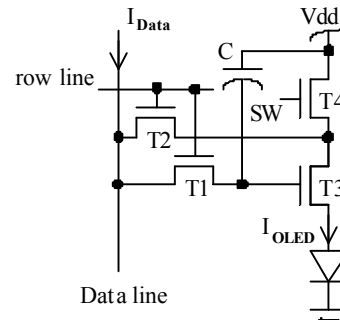


Figure 4. An a-Si current data pixel circuit.

While a-Si is able to produce steady state currents suitable for reasonable brightness levels, the terminal voltages are fairly large. As a result, the circuit in figure 3 may not be suitable for large format displays having a wide luminance range.

Unlike LCD column drivers incorporating voltage data, current data AMOLED drivers do not exist commercially. The magnitude of current depends upon display format and pixel design. Standardizing current column drivers may be difficult and may limit use of current data circuits.

4. Voltage Data Pixel Circuits

If LCD column voltage data drivers could be used, then panel design for different formats and panel sizes would be simpler and very similar to LCDs.

While figure 1 shows 2 simple voltage data pixel circuits, figure 5 shows a voltage data pixel that provides compensation for threshold voltage of the drive transistor¹⁰. The functionality of T1 through T4 function is identical to that in the current data pixel circuits. However, the driving method is more complex in that T3's threshold voltage must be established on the capacitors

before writing data. With the SW input low the row line is brought low with Vdd on the data line. Then, AZ is set low turning T2 on. A voltage across capacitor is developed that T3 forces to conduct. The SW input is brought high turning T4 off to isolate the circuit from the OLED. With T2 on, a voltage that is proportional to the threshold voltage of T3 is developed across both capacitors. The AZ input is brought high turning T2 off. The data voltage for luminance is then presented on the data lines. A portion of the data voltage is coupled onto the capacitor C by capacitor Cc. The row line is brought high followed by a low on the SW input turning T4 on. The OLED current is, to a first order, proportional to the square of the C's coupled data voltage.

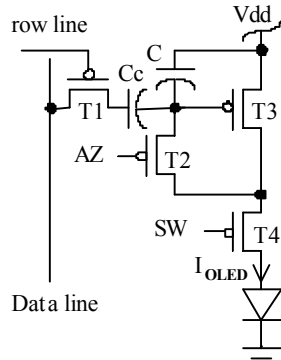


Figure 5. Data voltage pixel with threshold compensation

Assuming conventional addressing, there needs to be a pair of SW and AZ inputs and drivers for each row. Simulations have shown that there is not sufficient time to accurately set threshold voltage and write data within a row time.

5. A New Driving Method

It is desirable to have simpler V_t correcting circuits with a simple driving method. In addition, it is desirable to have opposite polarity device terminal voltages in order to reduce the effects of electrical stress and prolonging life of the TFT-OLED panel.

Figure 6 shows a modified voltage follower circuit shown in figure 1a that with the proper signals and timing can correct for threshold voltage. The storage capacitor is placed across the gate to source terminals of T3 for storing both T3's threshold voltage and the data voltage.

Figure 7 shows a set of signals and timing for threshold voltage compensation. Capacitance coupling due to switching is not shown to simplify discussion. Alternating the cathode voltage Vca polarity establishes alternating TFT terminal voltages.

The frame time is broken up into 3 periods. The first period is for setting the threshold voltage on the pixel capacitors and is this example $\sim 1.5\text{ms}$ long. The second period is for writing data and is $\sim 7.5\text{ms}$ long. The rest of the frame time, $\sim 7.5\text{ms}$, is for exposing or displaying the image.

There are three steps to establishing a threshold voltage on the storage capacitor C. First, while the cathode voltage, Vca, is at -18V , the AZ input is high for a short period. This establishes a capacitor voltage that is larger than the threshold voltage. Second, Vca is brought high to $+10\text{V}$. T3 conducts resulting in -10V across the OLED. Third, Vca is then set at 0V and the AZ input is

brought high. T3 conducts until a voltage that is approximately T3's threshold voltage is established on the capacitor. A negative threshold voltage is established across the OLED.

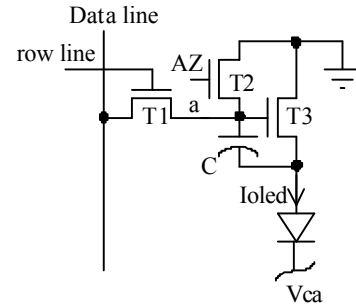


Figure6. Modified voltage follower pixel circuit

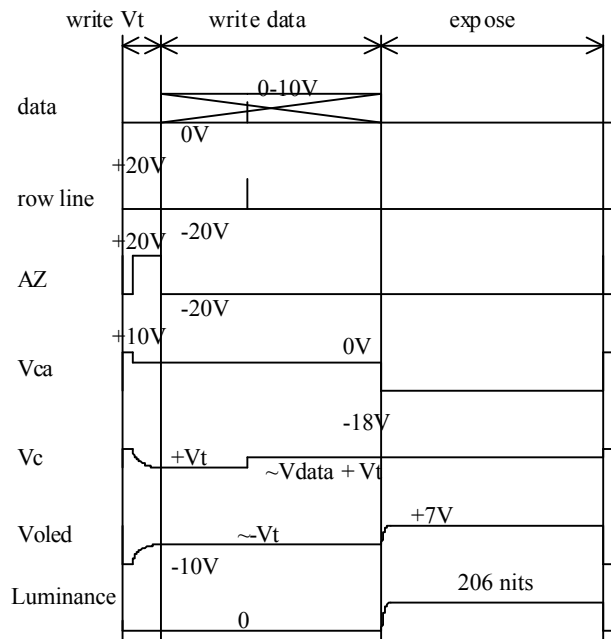


Figure 7. Signal timing diagram for V_t compensation

Data is written into the pixel circuit while Vca is at 0V and the AZ input is low. Assuming that the OLED voltage doesn't change while data is being written, the storage capacitor voltage is $V_{\text{data}} + V_t$. After data has been written to all the rows in the display, Vca is brought down to -18V . T3's current is proportional to $(V_{\text{data}} + V_t - V_t)^2$ or just $(V_{\text{data}})^2$.

Figure 8 shows the simulated luminance as a function of data voltage for the voltage follower in figure 1a driven in the usual manner and for the circuit shown in figure 6 using the driving method shown in figure 7. The new driving method produces higher luminance by accounting for V_t .

A model for a 100dpi color OLED having a luminous efficiency of $\sim 4\text{cd/A}$ and $\sim 500\text{cd/m}^2$ at $\sim 7\text{V}$ is used. The OLED off and reverse bias currents are low enough so as not to interfere with the pixel circuit operation.

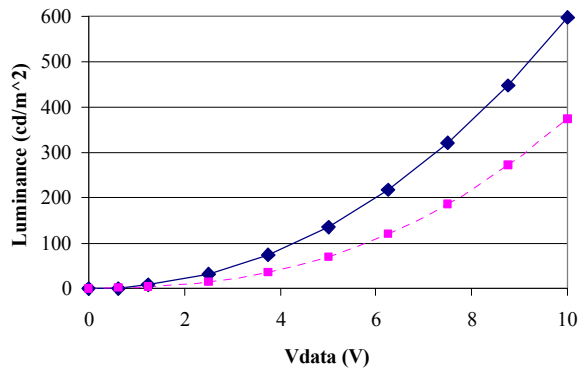


Figure 8. Luminance with data voltage for the modified voltage follower (solid) and standard voltage follower (dashed) circuits

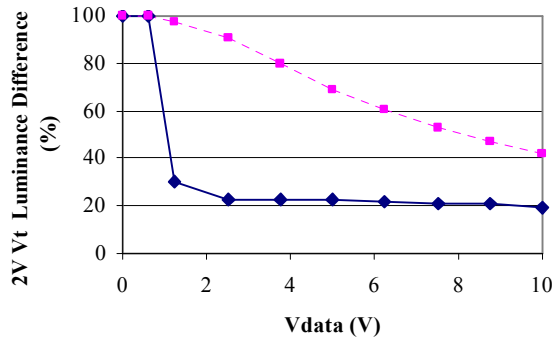


Figure 9. Luminance difference with data voltage for the modified voltage follower (solid) and standard voltage follower (dashed) circuits

Figure 9 shows the simulated percentage difference in luminance due to a 2V change in threshold voltage. A significant improvement is shown over all of the data voltage range. While the error increases for data voltage below 2.5V, the luminance is low and below 30cd/m². The luminance error remains constant at ~20% for data voltages above 2.5V. Most of the error occurs while writing. T3 conducts trying to drive the OLED voltage to 0V. T3 operates in the linear regime and current is proportional to T3's V_t , V_{data} and T3's transconductance. Another source of error occurs when V_{ca} is brought low for illumination. The OLED voltage changes from $-V_t$ to being forward biased. Different threshold voltages couple a different amount of charge onto the storage capacitor resulting from the stray TFT capacitance at node a. The resulting error here is ~20% of the difference in threshold voltage.

Improvement in the threshold compensation is possible. With higher OLED luminous efficiency, for example 10cd/A, the current would be 2.5 times lower. This would allow reducing the T3's W/L that would also reduce the luminance error by 2.5 times. In addition, other possible pixel circuit configurations may reduce the V_t compensation errors to less than 5%.

6. Summary

A new, not previously reported, AMOLED pixel driving method is shown. Readily available LCD column drivers can be used. With modified voltage follower pixel circuits, the luminance error due to threshold voltage variations is significantly reduced. For the most part, the pixel TFT and OLED terminals have opposite polarity voltages applied which tend to reduce transistor parameter variations due to electrical stress.

7. References

- [1] C. W. Tang, and S. A. Van Slyke, *Appl. Phys. Lett.* 51, 913 (1987).
- [2] T. Tohma, SID Proc. IDRC 1997, F1-F4.
- [3] G. Gu and S. R. Forest, Design of Flat-Panel Displays Based upon Organic Light-Emitting Devices, *IEEE Journal of Selected Topics in Quantum Electronics*, Vol. 4, No. 1, p83-99 (1998).
- [4] T. Van de Biggelaar, I. Camps, M. Childs, Martin Fleuster, A. Giraldo, S. Godfrey, I. M. Hunter, M. T. Johnson, H. Lifka, R. Los, A. Sempel, J. M. Shannon, M. J. Trainor, R. W. Wilks and N. D. Young, Passive and active matrix addressed polymer light emitting diode displays, *Flat Panel Display Technology and Display Metrology II, Proceedings of SPIE*, Vol. 4295, p134-146, (2001).
- [5] M. Mizukami, K. Inukai, H. Yamagata, T. Konuma, T. Nishi, J. Koyama, S. Yamazaki, T. Tsutsui, 6-Bit digital VGA OLED, *SID 00 Digest*, p912-915, (2000).
- [6] T. Sasaoka, M. Sekiya, A. Yumoto, J. Yamada, T. Hirano, Y. Iwase, T. Yamada, T. Ishibashi, T. Mori, M. Asano, S. Tamura, T. Urabe, A 13.0-inch AM-OLED display with top emitting structure and adaptive current mode programmed pixel circuit (TAC), *SID 01 Digest*, p384-387, (2001).
- [7] R. M. A. Dawson, Z. Shen, D. A. Furst, S. Connor, J. Hsu, M. G. Kane, R. G. Stewart, A. Ipri, C. N. King, P.J. Green, R. T. Flegal, S. Pearson, W. A. Barrow, E. Dickey, K. Ping, S. Robinson, C. W. Tang, S. Van Slyke, F. Chen, J. Shi, M. H. Lu, J. C. Sturm, The impact of the transient response, of organic light emitting diodes on the design of active matrix OLED displays, *IEEE IEDM 98*, p875-878, (1998).
- [8] T. Van de Biggelaar, I. Camps, M. Childs, M. Fleuster, A. Giraldo, S. Godfrey, I. M. Hunter, M. T. Johnson, H. Lifka, R. Los, A. Sempel, J. M. Shannon, M. J. Trainor, R. W. Wilks, N. D. Young, Passive and active matrix addressed polymer light emitting diode displays, *Proceedings of SPIE*, vol. 4295, p134-140, (2001).
- [9] Y. He, R. Hattori, J. Kanicki, Electrical reliability of two and four a-Si:H TFT pixel electrode circuits for active matrix OLEDs, *SID 00 Digest*, p 354-357, (2000).
- [10] R. M. A. Dawson, Z. Shen, D. A. Furst, S. Connor, J. Hsu, M. G. Kane, R. G. Stewart, A. Ipri, C. N. King, P.J. Green, R. T. Flegal, S. Pearson, W. A. Barrow, E. Dickey, K. Ping, S. Robinson, C. W. Tang, S. Van Slyke, F. Chen, J. Shi, J. C. Sturm, M. H. Lu, Design of an improved pixel for polysilicon active-matrix organic LED display, *SID 98 Digest*, p11-15, (1998)