Design of Organic TFT Pixel Electrode Circuit for Active-Matrix OLED Displays

Aram Shin, Sang Jun Hwang, Seung Woo Yu, and Man Young Sung(1)
Semiconductor and CAD Lab., Department of Electrical Engineering
Korea University, Seoul, Korea

***Abstract*—A new current-programming pixel circuit for active-matrix organic light-emitting diode (AM-OLED) displays, composed of four organic thin-film transistors (OTFTs) and one capacitor, has been designed, simulated and evaluated. The most critical issue in realizing AM-OLED displays with OTFTs is the variation and aging of the driving-TFTs and degradation of OLEDs. This can cause image sticking or degradation of image quality. These problems require compensation methods for high-quality display applications, and pixel level approach is considered to be one of the most important factors for improving display image quality. Our design shows that the current OLED and OTFT technology can be implemented for AM-OLED displays, compensating the degradation of OTFT device characteristics.**

***Index Terms*— active-matrix organic light-emitting diode (AM-OLED), organic thin-film transistor (OTFT), pixel circuit, current-programming, SPICE, simulation analysis.**

I. INTRODUCTION

Organic thin-film transistors (OTFTs) are presently of compelling interest due to their advantages over poly-Si and a-Si TFTs such as low temperature process and integration with flexible plastic substrates. Also, since the performance of pentacene based TFTs has become very close or even better than a-Si TFT devices, many research groups have demonstrated in employing OTFTs on organic light-emitting diode (OLED) displays[1,2]. This would lead to an all-organic display having the possibility of realizing low-cost electronics for large area applications.

Usually active-matrix OLED (AM-OLED) displays are realized using poly-Si or a-Si TFT technology, because the characteristics have improved and are very stable due to the advancement of liquid crystal display (LCD) technology. However, in order to fabricate large AM-OLED display arrays, OTFTs are considered best since low temperature fabrication is possible, which means low cost in the industry. Difficulty still lies in OTFT based AM-OLED design where the deviation and aging of device properties result in image sticking or non-uniform image quality. Also, the unstable characteristics of OTFT devices such as large threshold voltage variation (Δ Vth) and mobility degradation cause unstable operation, and hence resulting in non-uniform brightness of OLED. In order to guarantee reliable operation of AM-OLEDs, a pixel compensation scheme, making the circuit less sensitive to the large deviations of OTFT devices, is essential in obtaining high quality image.

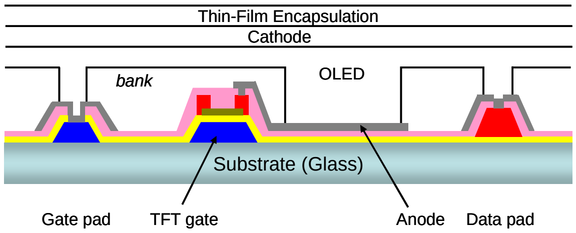

Figure 1. Schematic cross section of OTFT application with OLED.

In this paper, progress is made in driving AM-OLED displays less sensitive to the highly unstable OTFTs for large displays. It consists of four organic TFTs and one capacitor, three control lines and one power line. The operation method is discussed with simulation results to evaluate its performance. This work could be both set as a goal and as basic research information for future OTFT based AM-OLED development.

II. MODELING OF OTFT AND OLED

A. *Modeling and Application*

Due to the early development of LCD technology using polycrystalline and amorphous silicon TFTs, the physical properties of these devices are well known with precise models for industry level applications. However, since OTFTs are processed with many kinds of materials, there still lie some difficulties in precise modeling and extracting SPICE parameters. Also, the behaviors of organic materials are not yet clearly understood such as non-linear current with increase of gate voltage, thus leading to difficulties in establishing accurate formulas for modeling.

Fig. 1 shows the cross section of OLED application with OTFT on glass substrate. Since the process temperature of OTFTs is low, flexible plastic substrates

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The authors are with the Department of Engineering, Korea University, Seoul 136-701, Korea (corresponding author(1) e-mail: semicad@korea.ac.kr)

could be implemented for future displays. However, the characteristics of OTFTs have not yet met the requirements for high performance AM-OLED displays. The low mobility of organic materials, non-uniformity between the transistors, large variation of threshold voltage, and low reproducibility lie as the main barriers in applying OTFTs in AM-OLED displays.

B. Modeling of OTFT and OLED

Since the purpose of this work is to evaluate the operation of pixel circuits based on OTFT devices, the device characteristics used here could be set as goals for future OTFT based AM-OLED display applications. Also, since reliable OTFT characteristics could not be earned due to related process technology limitations, we have made some assumptions based on the current work found in literature. These device characteristics are expected to improve due to the technical improvements to be made in the future, yet in this work we have employed conventional characteristics for SPICE parameter extraction.

The OTFT model parameters were extracted using HSPICE MOSFET Model Level 3, based on pentacene TFT device characteristics. Since pentacene TFTs are p-type transistors, the model was based on hole mobility of 0.5 cm^2/Vs. While the mobility for pentacene is reported to exceed 1 cm^2/Vs[5], we have employed lower values for more practical results. The threshold voltage of -2.5 V with maximum drift velocity of 5.0×10^4 m/s was reasonable. The on/off ratio of 10^7 and dielectric thickness of 4000 Å was needed for pixel application. Also, the gate-drain and gate-source overlap capacitance was calculated to be 124 pF, respectively. The mobility modulation coefficient of -0.07 V^{-1} was applied considering the short channel effects. Fig. 2 and fig. 3 show the output and transfer characteristics of the OTFT device.

For OLEDs, among the various equivalent models [5,6,7], we have selected a simple and effective model which is a diode connected n-type MOS transistor with one capacitor as in Fig 10. The importance of precise modeling of OLEDs lies in the fact that the OLED capacitance has large effects on the operation of pixel circuits. Also, it determines the design parameters of the pixel circuit. The OLED parameters were extracted by fitting experimental work based on recent literature [3]. The OLED capacitance was based on the capacitance per area of conventional OLEDs, which is 25 pF/cm^2 for 100 um × 100um area. In this work we have applied 3 pF for more practical reasons.

III. PRINCIPLES OF COMPENSATION PIXEL CIRCUIT

Fig. 4 shows some basic pixel structures for OLED application. Fig. 4(a) is suitable for low power consumption since there are no VDD lines for power supply. However, this scheme cannot be operated by an active-matrix mode since the OLED current is off when the TFT M1 is off. Fig. 4(b) is a conventional AM-OLED pixel circuit which consists of two TFTs and one capacitor. Due to the non-stable OTFT characteristics such as threshold voltage shift and mobility degradation, a compensation technique must be introduced to obtain high quality image.

The proposed pixel circuit and its timing diagram are shown in Fig. 5 and 6. The scheme is based on the former work presented by Hattori *et al.* [4]. It is a current-programmed pixel structure which consists of four OTFTs and one capacitor. The terms M1, M2, and M4 are the switching TFTs, and M3 is the driving TFT in order to drive the OLED with the applied current.

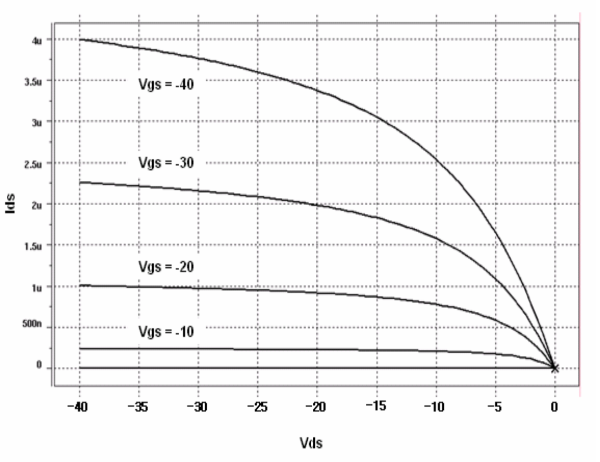


Figure 2. Output (Vds-Ids) characteristics of the OTFT model in this simulation at Vgs = -10, -20, -30, and -40V.

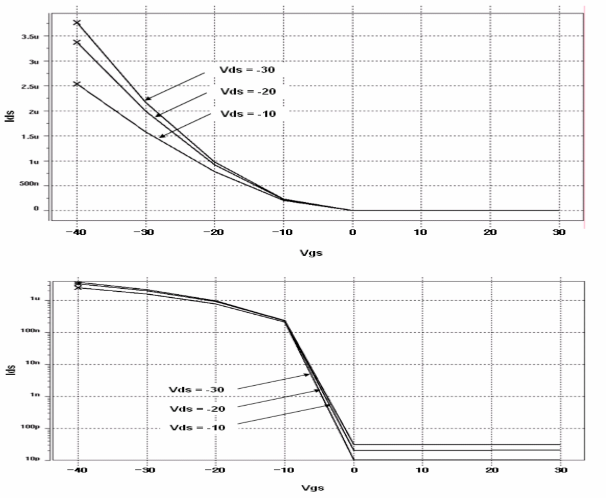
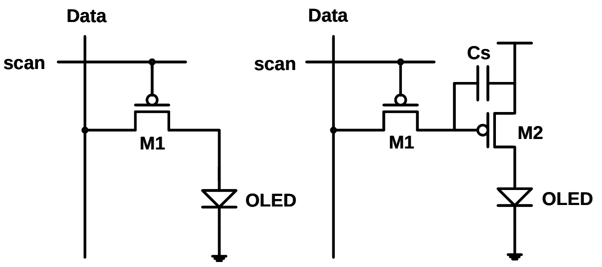


Figure 3. Transfer (Vgs-Ids) characteristics (linear, log) of the OTFT model in this simulation at Vds = -10, -20, and -30V.



(a) (b)

Figure 4. Suitable design for pixel circuit by p-type TFT: (a) 1T configuration; (b) 2T1C configuration.

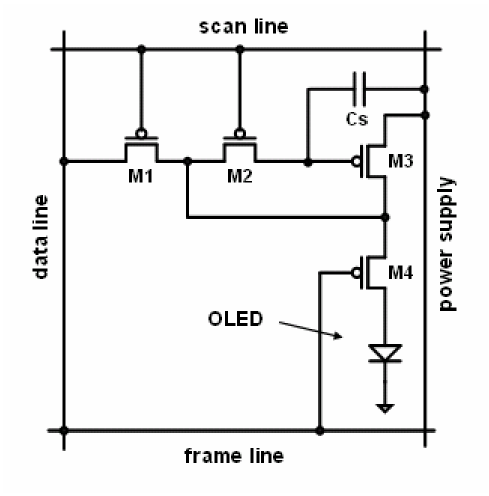


Figure 5. Proposed current-programmed pixel circuit. It consists of 4 organic transistors and one capacitor.

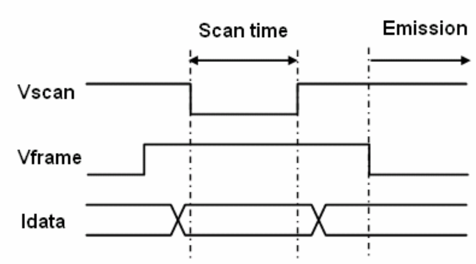


Figure 6. Example of timing diagram for the proposed pixel circuit.

The signal lines; data line, scan line and frame line are controlled as pulsed signals. As can be seen from the figure, the circuit is designed by aligning the two switching TFTs together to reduce the leakage current at the gate of the driving TFT. Also, this pixel design could both reduce the programming time of low-level current and the leakage current in the pixel.

The proposed pixel circuit is operated in two states; namely, programming state and emission state.

A. Programming state

This period is for charging the gate voltage of driving TFT M3 to the level of input data current (Idata). When the scan signal (Vscan) is low (M1 and M2 are ON), M3 operates in saturation mode due to the diode-connection of M2. Thus, forming a current path from the VDD power supply through transistors M1 and M2 and to the data current (Idata). Hence, the gate voltage of M3 is set by the input current level and is stored in capacitor (Cs) as shown in (1) and (2).

$$I_{DATA} = \beta_3 \left(V_{dd} - V_{g\_M3} - |V_{TH3}|\right)^2 \qquad (1)$$

$$V_{g\_M3} = V_{dd} - \left(|V_{TH3}| + \sqrt{\frac{I_{DATA}}{\beta_3}}\right) \qquad (2)$$

Where, $\beta_3 = 0.5 \cdot \mu \cdot C_{ox} \cdot (W/L)_3$, μ is the hole mobility of the OTFT, C_{ox} is the oxide capacitance. The gate voltage of driving TFT M3 becomes dependant on the input data (Idata). If the threshold voltage shifts due to degradation of OTFT, the gate voltage of M3 will also shift in order to maintain the same amount of current flow as input data (Idata). Any other parameter shifts such as mobility degradation or Vdd line voltage drop will result in identical shift of gate voltage in order to maintain the applied input data (Idata). Thus, this type of scheme is referred to current programming compensation.

TABLE I.
OPTIMIZED DESIGN PARAMETERS FOR THE PROPOSED PIXEL CIRCUIT

Design Parameters	**Unit**	**Value**
$(W/L)_1$	um	150 / 5
$(W/L)_2$	um	7 / 5
$(W/L)_3$	um	575 / 5
$(W/L)_4$	um	100 / 5
Cs	pF	5
Vscan	V	-25 – 0
Vframe	V	-25 – 0
Idata	uA	2 – 8

B. Emission state

After programming the gate voltage of M3, the same amount of current must be supplied to the OLED. This is realized by changing the scan signal (Vscan) high (M1 and M2 are OFF) and the frame signal (Vframe) low (M4 is ON) and thus, the same level of current will flow through the OLED.

C. Optimization

Optimization is a difficult process because operation of the pixel circuit is very sensitive to the sizes (W/L) of OTFTs. Since the sizes of the OTFTs (in this case width) are large as 575 um, the internal capacitance of TFTs greatly affect on the operation due to charge injection and clock feed-through effects. In order to minimize these dynamic effects we have minimized the sizes (W/L) of the OTFT to an optimized value. Optimization was done under a statistical method called "Design of Experiment (DOE)," concerning the interaction between theses parameters. By applying this method we were able to optimize by fixing the least interacting parameter to a reasonable value and determine the next least interacting parameter, and so forth. Table 1 lists the optimized design parameters for the pixel circuit.

IV. SIMULATION RESULTS

To verify the operation and performance of the pixel circuit, SPICE simulation was conducted with Star-Hspice circuit simulator. Based on the modeling results of OTFTs and OLEDs, we have evaluated its linearity properties and its compensation of threshold voltage shift and mobility.

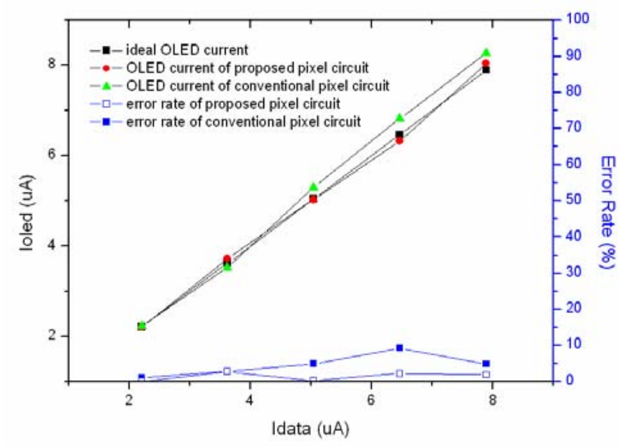


Figure 7. Relationship between the input current (Idata) and the output OLED current (Ioled)

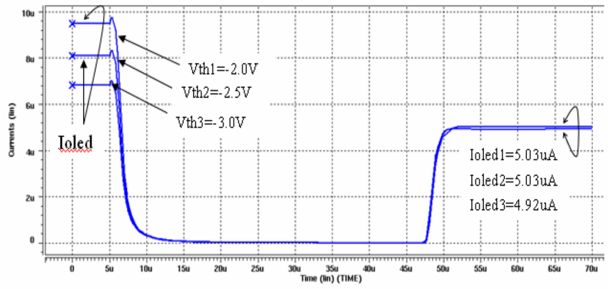


Figure 8. Transient response results with respect to threshold voltage degradation of driving TFT M3.

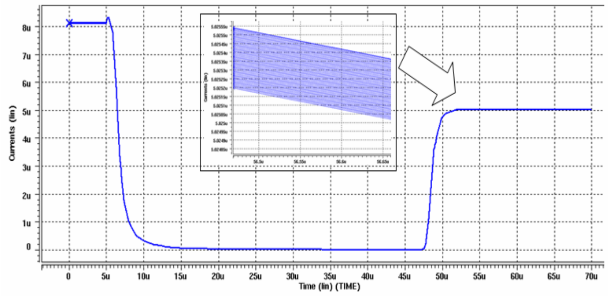


Figure 9. Transient response results with respect to mobility degradation of driving TFT M3.

Fig. 7 shows the relationship between the input current (Idata) and the output OLED current. The input data range was limited to 2 uA to 8 uA since this range is sufficient for OLED illumination and low current levels are more difficult to control in large-area AM-OLED displays[7]. The Error rate is measured by $\Delta I_{OLED} / I_{OLED}$ (%) with optimized sizes (W/L) of the proposed and conventional pixel circuits. The error rate shows improvement of linearity to as low as 1 % error, compared to conventional pixel circuit with maximum error rate of 10%. Fig. 8 shows the transient response with respect to gate bias stress resulting in threshold voltage shift of the driving TFT M3. The threshold voltage deviation of a-Si:H TFTs is reported to be around 0.33 V[3], therefore, in this work we have set the OTFT threshold voltage shift to 1 V, which is quite reasonable. As can be seen from the figure, the output OLED current has negligible current difference with threshold voltage difference of 0.5 and 1 V, respectively. Therefore, the threshold voltage shift of driving TFT is fully compensated by the pixel circuit. Fig. 9 shows the transient response with respect to mobility degradation of driving TFT M3. The mobility variation was from 0.005 cm^2/Vs to 0.5 cm^2/Vs. This shows reliable output OLED current even if the mobility of driving TFT degrades to very low values (1% of initial value).

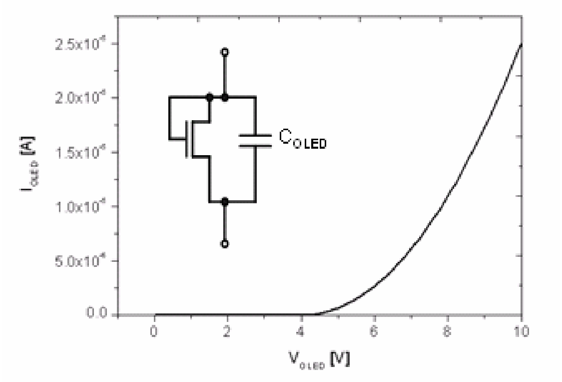


Figure 10. Simulated I-V characteristics of conventional OLEDs. The value of C_{OLED} is 3pF

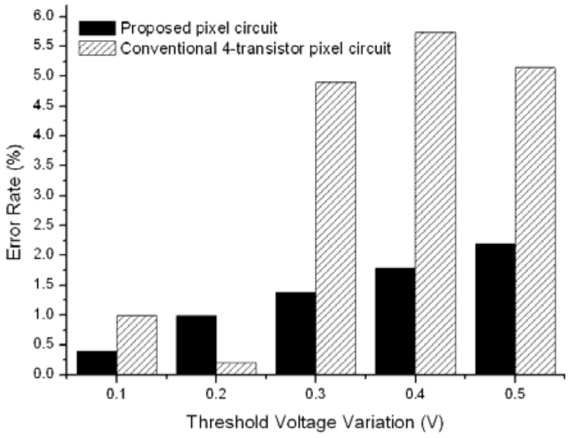


Figure 11. Error rates of OLED current with respect to threshold voltage variations.

Fig. 10 shows the simulated I-V curve OLED. It is based on the modeling of conventional OLED with diode connected n-type MOSFET and a capacitor (C_{OLED}). Fig. 11 shows the error rate of OLED current for the proposed pixel circuit compared to the conventional 4T1C pixel circuit. With threshold voltage variation of 0.1 to 0.5 V, the error rate of the proposed pixel circuit is minimized to less than 2% over the whole range while that of conventional 4T1C circuit exceeds 5.5 %. Since these results are compared with conventional 4T1C pixel circuits, the results could be more comparative if conventional non-compensating 2T1C circuits were considered.

V. CONCLUSION

We have proposed a new AM-OLED pixel design, which consists of four organic TFTs and one capacitor, and verified the operation using SPICE simulation. The new pixel design suppresses the leakage current more effectively by aligning the two switching TFTs together, so as to ensure linearity between input data and OLED current. The simulation results show that the proposed pixel circuit compensates the threshold voltage degradation of driving TFT with error rate less than 1% over the entire data range. These results verify the possibility of realizing low-cost, large-area OTFT-based AM-OLED displays.

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Aram Shin received his BS degree in Electrical Engineering from Korea University, Seoul, Korea in 2006. He is currently a graduate student in the Department of Electrical Engineering at Korea University. His research interests include active-matrix OLED display design using amorphous and poly-silicon TFTs, reliability and device characteristics of organic thin-film devices, and driving circuits for AM-LCD and AM-OLED displays.

Sang Jun Hwang received his BS and MS degrees in Electrical Engineering from Korea University, Seoul, Korea, in 1994 and 1996, respectively. He is currently a Ph.D. candidate and researcher in the Department of Electrical Engineering at Korea University. His current research interests are in the area of active-matrix OLED display design based on poly-silicon TFTs, driving circuits for flat panel displays, and high speed DRAM design.

Seung Woo Yu received his BS degree in Electrical Engineering from Korea University, Seoul, Korea, in 2003. He is currently a graduate student in the Department of Electrical Engineering at Korea University. His current research interests are with semiconductor device and process designs based on computer-aided design and driving circuits for flat panel displays.

Man Young Sung received the M.S and Ph.D. degrees in electrical engineering from Korea University, Seoul, Korea, in 1977 and 1981, respectively.

From 1986 to 1988, he was an Associate Professor in the Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign. In 1991, he served as Visiting Scientist at Royal Institute of Technology, Sweden. In 1989, he joined the Department of Engineering, Korea University, Seoul, Korea, where he was Vice President of Student Affairs from 2000 to 2002. He is currently Professor in the Department of Electrical Engineering at Korea University. His current research interests are in the area of power semiconductor devices, TFT device reliability and characteristics, and driving circuits for flat panel displays such as TFT-LCD and AMOLED.