13.2: A Floating-Gate OTFT-Driven AMOLED Pixel Circuit for Variation and Degradation Compensation in Large-Sized Flexible Displays

Tsung-Ching Huang¹, Koichi Ishida¹, Tsuyoshi Sekitani², Makoto Takamiya¹, Takao Someya², and Takayasu Sakurai¹

¹Institute of Industrial Science, University of Tokyo, Japan
²Department of Electrical Engineering, University of Tokyo, Japan

Abstract
For the first time, we demonstrate an AMOLED pixel circuit on a 13-μm thick plastic film that applies floating-gate organic TFTs (FG-OTFTs) to compensate for OTFT driving current variations and OLED efficiency degradations. By programming V_{TH} of the FG-OTFTs, we can realize less than 5% spatial non-uniformity and 85% power reduction compared with voltage-programming.

1. Introduction
AMOLED displays have attracted much attention recently because of their excellent image quality and wide viewing angle [1-2]. Organic TFT (OTFT) is considered as a strong candidate for pixel circuits of large-size flexible displays, because of its mechanical flexibility and compatibility with the low-cost printing process at room temperature [3-4]. OTFT-driven AMOLED displays, therefore, are a promising solution for realizing next-generation large-size, light-weight, and mechanically robust flexible displays. To print a large number of OTFTs on large-area flexible substrates with high-uniformity, however, is very challenging and has become the major bottleneck for realizing large-size OTFT-driven AMOLED flexible displays.

In this paper, for the first time, we demonstrate a FG-OTFT-driven AMOLED pixel circuit for flexible displays as shown in Fig. 1. The pixel circuit enables electrical feedback to tune V_{TH} of the FG-OTFT for compensating OTFT variations and OLED efficiency degradations. Unlike voltage-programming or current-programming [5-6] that require V_{TH} compensation in every frame time, the programmed V_{TH} in our FG-OTFTs can retain for tens of hours and no further V_{TH} programming is needed within the retention time. The proposed work, therefore, has several key advantages over conventional methods including: 1) low power-consumption by eliminating V_{TH} compensation cycle in the frame time, 2) compensation for both OTFT non-uniformity and OLED efficiency degradations, and 3) higher aperture ratio and yield because of reduced transistor counts (3T-1C).

1.1. Floating-Gate Organic TFTs
Fig. 2 shows the cross-section of a 20V FG-OTFT. The channel length L is 20 μm and the organic semiconductor in our p-type FG-OTFT is DNTT [7] with carrier mobility of 0.7 cm²/Vs. While the 20V FG-OTFT can work as a normal OTFT with -20V gate-voltage V_{GS}, its V_{TH} can be adjusted by applying high-voltage electrical stresses to the gate terminal. As shown in Fig. 3, when the source and drain terminals of a FG-OTFT are grounded and no drain-source current is conducting, the electron holes can be injected from the Parylene gate insulator to the Au floating gate by applying a pulsed high voltage such as -60V to its gate terminal. These injected holes can be kept in the Au floating-gate and reduce electrical field from the gate voltage to the organic semiconductor. The effective V_{TH} of the FG-OTFT is therefore increased until the injected electron holes completely escape. More details about our FG-OTFTs can be found elsewhere in [8].

Figure 1: Proposed AMOLED 3T-1C pixel-circuit.

Figure 2: Cross section of a 20V FG-OTFT.

Figure 3: Working principle of a FG-OTFT.
1.2. Pixel Structure

Fig. 4 shows typical voltages of $V_{\text{DATA}}$, $V_{\text{SCAN}}$, $V_{\text{MON}}$, and $V_{\text{SENSE}}$ in Fig. 1 for monitoring FG-OTFT non-uniformity and OLED efficiency degradations, as well as programming $V_{\text{TH}}$ of the FG-OTFT. In order to monitor the driving current of $T_D$ as shown in Fig. 4 without being affected by $V_{\text{TH}}$ variations of $T_M$, $V_{\text{CAL}}$ was set sufficiently close to $V_{\text{TH}}$ of $T_D$ while $V_G$ of $T_M$ was set to a higher voltage such as -40V to keep the on-resistance of $T_D$ much higher than that of $T_M$ as shown in Fig. 4(a). Fig. 5 shows SPICE-simulated $T_D$ current measurement errors due to $V_{\text{TH}}$ variations of $T_M$. We can find that the current measurement error can be minimized to less than 5% even under 20% $V_{\text{TH}}$ variations of $T_M$ because the measured current was mainly determined by $T_D$ in the saturation region rather than $T_M$ in the linear region. Fig. 4(b) shows the configuration of monitoring OLED efficiency degradation. $T_D$ was switched off by setting $V_{\text{GS}}$ of $T_D$ to be 10V and $V_{\text{SENSE}}$ was set close to $V_{\text{TH}}$ of OLED (~6V) to minimize $V_{DS}$ of $T_M$ for reducing current measurement errors. The OLED efficiency degradation can then be estimated by measuring $V_{\text{TH}}$ of OLED at a given current. $V_{\text{DATA}}$ and $V_{\text{TH}}$ of $T_D$ can be adjusted accordingly to compensate for OLED efficiency degradations.

Fig. 4(c) shows the configuration of $V_{\text{TH}}$ programming for $T_D$. A pulsed electrical stress -60V was applied to the gate terminal of $T_D$ through $T_S$. $V_D$ and $V_S$ of $T_D$ were both set to 0V during $V_{\text{TH}}$ programming such that no current is conducting through $T_D$. The measurement results and the scheme of $V_{\text{TH}}$ programming for minimizing non-uniformity and power consumption are followed.

2. Measurement Results

2.1. $V_{\text{TH}}$ Programming

Figure 4: (a) Monitoring FG-OTFT driving current, (b) monitoring OLED efficiency degradations, and (c) applying electrical stress for $V_{\text{TH}}$ programming. $W_{TD}=6$ cm, $W_{TM}=W_{TS}=0.3$ cm, and $C_S=2pF$ in our pixels.

Figure 6: $V_{\text{TH}}$ programming process for a FG-OTFT with (-60V, 75ms) step size of electrical stress.

To perform quantitative analysis of $V_{\text{TH}}$ programming, we applied a digital control method by fixing the stress voltage $V_{\text{STRESS}}$ to -60V and varying the number of stress pulses and the pulse-width for $V_{\text{TH}}$ control. Fig. 6 shows the measurement results of the FG-OTFT driving currents during $V_{\text{TH}}$ programming process with (-60V, 75ms) stress conditions. The device size of the FG-OTFT was made large to provide sufficient driving currents for our OLEDs to achieve peak brightness greater than 200 cd/m². From Fig. 6 we can observe that $V_{\text{TH}}$ increases with the stress time due to injected electron holes into the floating-gate. The programmed $V_{\text{TH}}$ can retain for tens of hours until full recovery to its original $V_{\text{TH}}$. Since $V_{DS}$ of the FG-OTFT was kept to 0V during $V_{\text{TH}}$ programming, the measured drain-source current $I_{DS}$ of $T_D$ during $V_{\text{TH}}$ programming was lower than 1nA, which was six orders or less than its saturation current and therefore consumed negligible power compared with OLED driving.
Fig. 7 shows the relationship among $\Delta V_{TH}$, stress pulse width, and stress time with -60V stress voltage. Here $V_{TH}$ is defined as $(W/L \times 50\text{nA})$ using the constant current method, where $W$ is the channel width and $L$ is the channel length. We can learn from Fig. 7 that larger stress voltage $V_{STRESS}$ and longer stress time $T_{STRESS}$ can result in greater $V_{TH}$ shifts. The measured $\Delta V_{TH}$ can be fitted to Eqn.1 where $\alpha$ and $\beta$ are fitting parameters.

$$\Delta V_{TH} = V_{Stress} \alpha \log_{\beta}(T_{Stress})$$

(1)

2.2. Variation Compensation for Pixel Circuit

To demonstrate variation compensation by $V_{TH}$ programming, we prepared six identical FG-OTFT-driven AMOLED pixels in a 2x3 array on the same polyimide plastic film. In order to illustrate the effects of electrical stress, Fig. 8 shows $I_{DRIVE}-V_{DATA}$ plots of two AMOLED pixels and the inset shows the variations before and after applying electrical stress. We can see that the driving current difference was larger than 15% initially and this difference was minimized to less than 2% after applying total 525ms stress with (-60V, 75ms) stress pulses. Note that the stress conditions can be further optimized to meet the requirements of $V_{TH}$ control resolution, total stress time, and required spatial uniformity. The $V_{TH}$ programming scheme for variations and degradations compensation is illustrated using a flowchart as shown in Fig. 9. $V_{TH}$ monitoring and electrical stress are provided through external circuitry. $T_D$ in Fig. 9 represents the FG-OTFT-based OLED driver as shown in Fig. 4. Fig. 10 shows the compensation results for all six AMOLED pixels. The broken lines represent the initial driving currents provided by FG-OTFTs before-stress while solid lines are driving currents after $V_{TH}$ programming, which scheme is illustrated in Fig. 9. The inset of Fig. 10 shows that the driving current variation, represented by standard deviations, was reduced from 14% to less than 5% after $V_{TH}$ programming. Although here only shows the results for total six pixels, the $V_{TH}$ programming scheme can be easily applied to all AMOLED pixels in flexible displays for minimizing spatial non-uniformity.

The OLED efficiency degradations can also be compensated by monitoring $V_{TH}$ of OLEDs at known input currents through $T_M$ as shown in Fig. 4(b), which can be used to indicate the degree of OLED efficiency degradations for $T_D$ current compensations.

Figure 7: The relationship between $V_{TH}$ shifts and pulse.

Figure 8: Variation compensations for two neighboring AMOLED pixels (blue and red solid-lines). Black broken-line shows the after-stress $I_{DRIVE}$ while blue solid-line shows the before-stress $I_{DRIVE}$ of the identical AMOLED pixel.

Figure 9: Flowchart of measuring and compensating OTFT variations and OLED degradations.

Figure 10: Driving currents $I_{DRIVE}$ of total six pixels before-stress (broken-line) and after-stress (solid-line). The inset shows the standard deviations of $I_{DRIVE}$. Green broken lines show no-need-to-stress pixels due to initially lower driving currents.
2.3. Power Reduction

In addition to variation and degradation compensation, the proposed FG-OTFT pixel circuit also lowers the pixel power consumption $P_{\text{PIXEL}}$ because of eliminating the $V_{\text{TH}}$ compensation cycle in the frame time $\tau_{\text{FRAME}}$ ($\tau_f$). For conventional compensation schemes such as voltage-programming, $V_{\text{TH}}$ of the driving TFT is generated and stored in a capacitor that needs to be updated every frame time. In order to ensure that the stored $V_{\text{TH}}$ is equal or close enough to the real $V_{\text{TH}}$, the required compensation time $\tau_{\text{COMPENSATION}}$ ($\tau_C$) should be longer than tens of microseconds ($\mu$s) [9]. Since $\tau_C$ reduces the driving time $\tau_{\text{DRIVING}}$ ($\tau_D$) as illustrated in Eqn. 2 for a given $\tau_f$ and the compensation power $P_{\text{COMPENSATION}}$ ($P_C$) does not directly contribute to driving the OLED, the required $P_{\text{PIXEL}}$ for the voltage-programming scheme within the reduced $\tau_D$ in order to achieve the same peak brightness as the proposed $V_{\text{TH}}$ programming scheme will therefore increase significantly. Fig. 11 shows the timing diagram and Fig. 12 shows the normalized pixel power consumption $P_{\text{PIXEL}}$ for both voltage-programming and $V_{\text{TH}}$ programming schemes. Note that $P_{\text{PIXEL}}$ in Fig. 12 is calculated by assuming $\tau_C$ equal to 5 $\mu$s and the same average OLED driving currents $I_{\text{LED}}$ under the same $\tau_D$ for both cases. While the proposed $V_{\text{TH}}$ programming scheme using FG-OTFTs does not require the $V_{\text{TH}}$ compensation cycle and consumes negligible power during the $V_{\text{TH}}$ programming process, the voltage-programming scheme requires 85% power overhead if driven at the XGA resolution with 120-Hz refresh rate. Higher resolutions and refresh rates, as well as longer $\tau_C$, will inevitably increase the pixel power consumption due to the reduced $\tau_D$. Note that for high refresh rates such as 240-Hz and 600-Hz, higher resolutions than VGA mode are unable to achieve in the voltage-programming scheme since $\tau_f$ will be less than 5 $\mu$s ($=\tau_C$).

$$P_{\text{PIXEL}} = P_{\text{COMPENSATION}} + P_{\text{PROGRAMMING}} + P_{\text{DRIVING}}$$

$$\tau_{\text{DRIVING}} = \tau_{\text{FRAME}} - \tau_{\text{COMPENSATION}} - \tau_{\text{PROGRAMMING}}$$

3. Conclusion

In this paper, for the first time, we demonstrate a FG-OTFT driven AMOLED pixel circuit on a 13-µm thick polyimide plastic film for compensating OTFT process variations and OLED efficiency degradations. The photo of the proposed FG-OTFT pixel-circuit is shown in Fig. 13. In our test sample, we prepared six identical pixels allocated in a 2x3 array. After applying the electrical stress to the driving FG-OTFTs, the overall spatial non-uniformity of the driving FG-OTFTs was minimized from 14% to be less than 5%. Compared with the conventional voltage-programming compensation scheme, the pixel power consumption can be reduced by 85% for the XGA resolution at 120-Hz refresh rate.

4. Acknowledgements

We will like to thank for Japan Science and Technology Agency (JST) / Core Research for Evolutional Science and Technology (CREST) for financial supports.

5. References