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Simultaneous Emission AC-OLED Pixel Circuit for Extended Lifetime of OLED Display

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ABSTRACT This paper demonstrates a pixel circuit of seven thin film transistors (TFTs) and two capacitors that drives an AC driven OLED (AC-OLED) at a simultaneous emission scheme. Because the AC-OLED is composed of two OLED units connected in opposite directions, the proposed circuit drives the current programmed once during a frame time in both ways. Since one OLED unit emits the light for about half frame time, the lifetime of OLEDs is ameliorated substantially. In addition, the proposed pixel circuit allows threshold voltage and supply voltage variations to be compensated. SPICE simulation results with a p-channel low temperature poly-silicon TFT model show that the average current non-uniformities are improved to 1.19% and 3.37% for threshold voltage and supply voltage variations of ±0.5 V, respectively.

INDEX TERMS AC-OLED, image-sticking, lifetime, TFT, simultaneous emission, compensation.

I. INTRODUCTION

Active matrix organic light emitting diode (AMOLED) displays have been studied and developed as a next-generation display technology due to large color gamut, fast response, high contrast ratio, small form factor, wide viewing angle, and flexibility [1], [2]. Currently, some panel makers have been paving the way for expanding AMOLED display applications from smartphones to TVs.

On the other hand, it is still required to tackle the critical drawbacks of AMOLED displays such as high manufacturing cost and poor lifetime [3]–[5]. Whereas prices of AMOLED displays are getting close to active matrix liquid crystal displays (AMLCDs) rapidly, insufficient lifetime is still remained as the difficult issue to resolve, especially, as to blue OLEDs. The poor lifetime is caused by efficiency degradation over the usage time, which brings out the image-sticking artifact on the screen. For an example illustrated in Fig. 1, suppose that after an OLED display is driven with a checker board pattern for a long time, the full gray pattern with a middle gray level is displayed. Because the white areas (B) of the checker board pattern suffer from the efficiency reduction, those areas (B’) show lower luminance than desired one at the full gray pattern. However, the black areas (A’) present desired luminance at the full gray pattern. Consequently, the checker board pattern is observed even at the full gray image after aging.

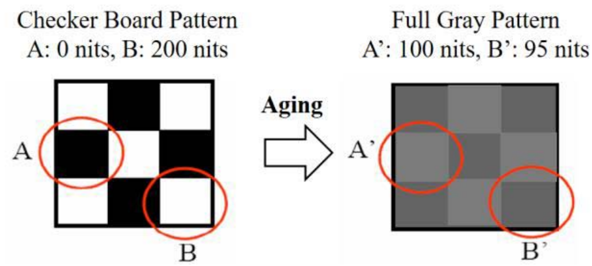

FIGURE 1. Image sticking artifact caused by aging with a checker board pattern.

Therefore, when some images are placed on the fixed positions of a screen for a long time, users would become annoyed due to the image-sticking artifacts. Especially, monitors and TVs should provide the good display quality for much longer years, which increases the possibility of image sticking occurrence substantially.

This issue has been addressed in the perspective of a device structure by adopting mixed host system, choosing appropriate material sets, controlling mobility, and adding exciton or carrier blocking layers [6]–[13]. In addition, compensation circuits have been developed to reduce the image-sticking artifacts without extending the lifetime of

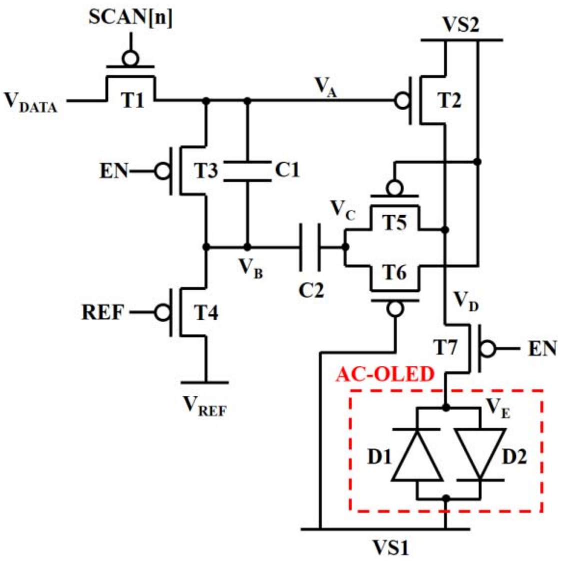

FIGURE 2. Schematic of a proposed AC-OLED pixel circuit.

an OLED device [14]–[16]. It has been also reported that an alternating current (AC) driving scheme can alleviate the efficiency degradation by applying the reverse bias to OLEDs [17]–[20]. On the other hand, the vertically stacked OLED structure has been introduced to control two OLED units independently by polarities of one AC driving voltage [21]. For the AC driven OLED (AC-OLED) in display applications, one unit can get biased reversely while the other unit emits the light at the forward bias. Because a unit experiences only half stress time along with the further improvement by reverse bias compared to a conventional OLED, the image sticking artifact can be ameliorated substantially.

This paper proposes a pixel circuit that compensates the threshold voltage variation of driving thin film transistors (TFTs) as well as supply voltage variation with AC-OLEDs at the simultaneous emission (SE) method [22]–[24] to achieve uniform display quality and long lifetime.

II. PROPOSED AC-OLED PIXEL CIRCUIT

A proposed pixel circuit is composed of seven p-channel TFTs (T1-T7) and two capacitors (C1, C2) as shown in Fig. 2. An AC-OLED is modeled with two OLEDs (D1, D2) connected in opposite directions to each other. The basic threshold voltage compensation concept is based on the previous circuit of five oxide TFTs and two capacitors [25].

The AC-OLED pixel circuit is driven at a SE scheme as shown in Fig. 3(a) with four periods of *Scan*, *Compensation*, *Emission1*, and *Emission2*. In the period of *Scan*, voltages are programmed into pixel circuits line-by-line and the threshold voltage variations of all driving TFTs over a panel are compensated at the same time in the following *Compensation* period without any light emission. Then, two emission periods of *Emission1* and *Emission2* flow the

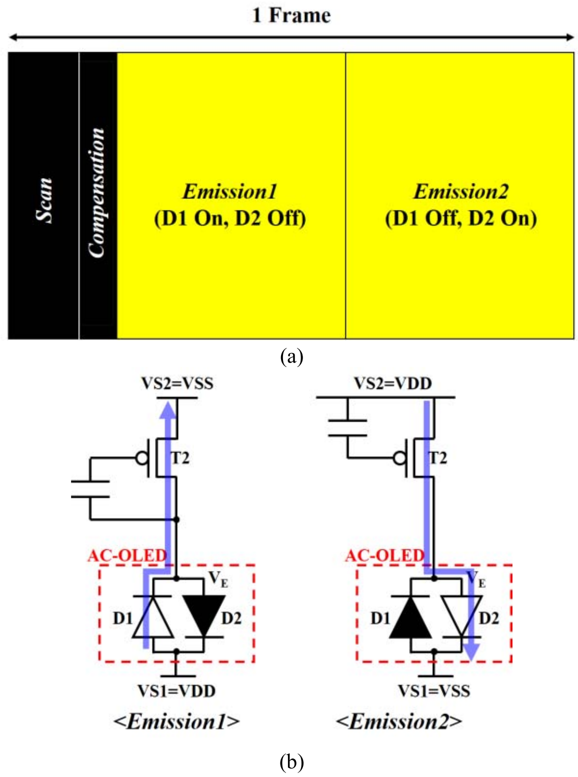

FIGURE 3. SE driving scheme for the proposed pixel circuit (a) four periods in a frame time: While black regions means no light emission, yellow regions represent the light emission. (b) equivalent circuits for two emission periods of *Emission1* and *Emission2:* Arrows indicate the current directions that are opposite to each other for *Emission1* and *Emission2*. The diode that is filled in black is turned off.

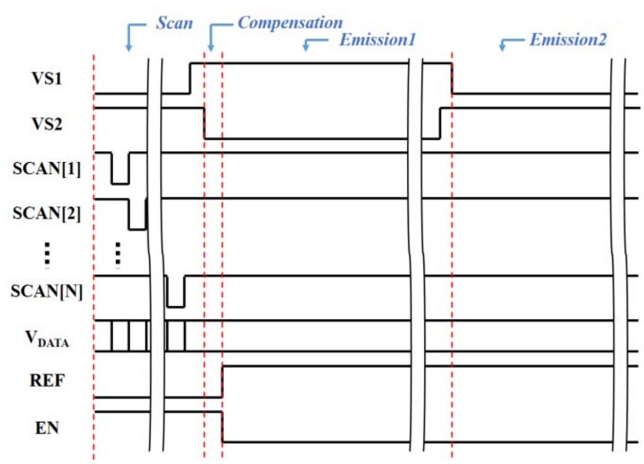

FIGURE 4. Timing diagram of AC-OLED pixel circuit.

programmed current through D1 and D2, respectively. The equivalent circuits in *Emission1* and *Emission2* are simply described in Fig. 3(b), where VDD and VSS are high and low supply voltages. The arrows indicate the directions of current flow for *Emission1* and *Emission2*. In *Emission1*, the current flows from VS1 to VS2 and D1 is turned on. In *Emission2*, the current runs from VS2 to VS1 and the light

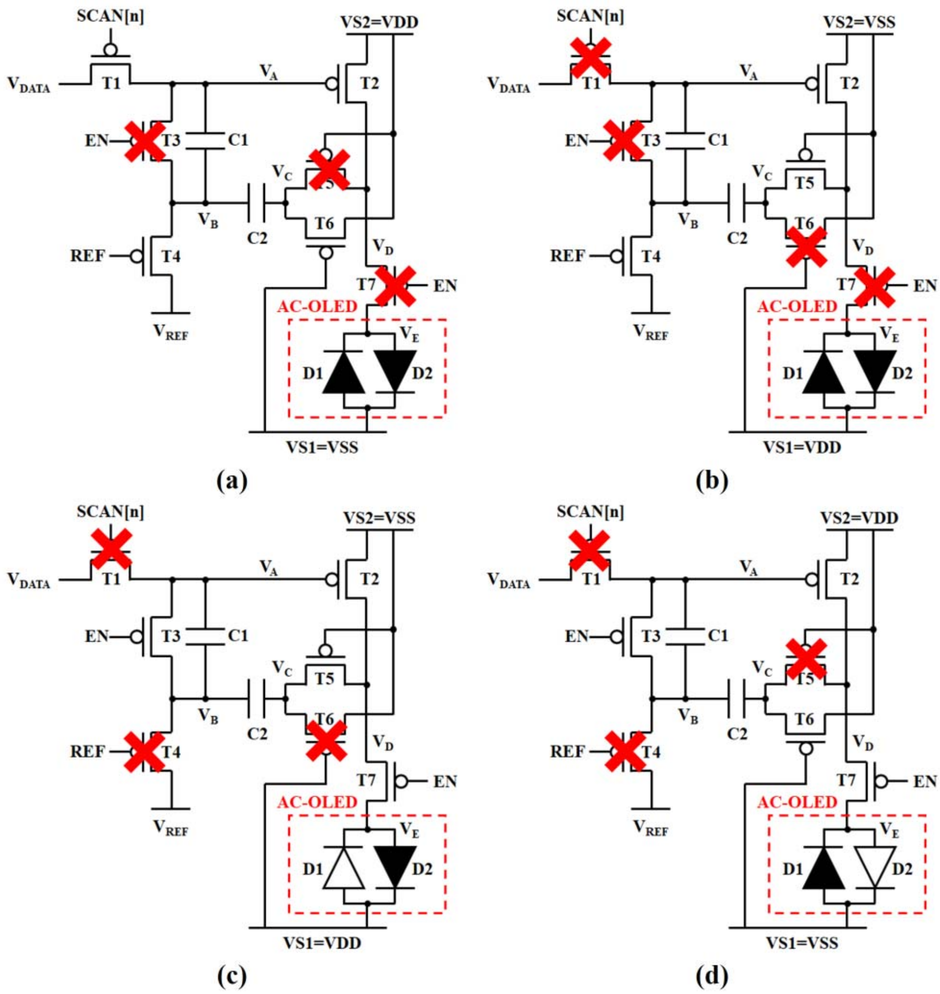

FIGURE 5. **Operations of proposed AC-OLED pixel circuit (a) *Scan* (b) *Compensation* (c) *Emission1* (d) *Emission2*. The diode that is filled in black is turned off.**

is emitted by D2. The overall timing diagram is presented in Fig. 4.

The four-period operation of the proposed circuit is explained in more detail as follows.

1) *Scan:* As shown in Fig. 5(a), VS1 and VS2 are provided at VSS and VDD, respectively. SCAN[n] and REF are driven at the low voltage and EN is set to the high voltage. T3, T5, and T7 are turned off by high voltages of VS2 and EN. The gate of T2 (V_A) is charged with V_{DATA} through T1 and V_B is driven by V_{REF} via T4. Because V_{DATA} is low enough to turn T2 on, V_D is initialized by VS2 of the high voltage level VDD. The voltage across C1 (V_A-V_B) is programmed as V_{DATA}-V_{REF} and the voltage of C2 (V_B-V_C) is set as V_{REF}-VDD. In this period, the AC-OLED is shut down without any light emission.

2) *Compensation:* VS1 and VS2 are changed to VDD and VSS, and SCAN[n] is driven at the high voltage as presented in Fig. 5(b). T1, T3, T6, and T7 are turned off. Because V_B is connected to the constant reference voltage V_{REF}, V_A is held at V_{DATA} and V_D is discharged through T2 until V_D becomes $V_{DATA} + |V_{TH2}|$ where V_{TH2} is the threshold voltage of T2. Therefore, the voltage across C2 (V_B-V_C) turns to be $V_{REF} - (V_{DATA} + |V_{TH2}|)$. Since EN is high, the AC-OLED is remained at an off state.

3) *Emission1:* As depicted in Fig. 5(c), low EN turns T3 and T7 on, and high REF turns T4 off. As V_A and V_B are shorted, the voltage across C2 (V_{REF}-$V_{DATA} - |V_{TH2}|$) becomes the gate-source voltage of T2. Consequently, the current (I_{OLED}) expressed in (1) flows through D1 in the AC-OLED, emitting the light. β is $\mu_p C_{ox}(W/L)_2$, μ_p is the hole mobility, C_{ox} is the oxide capacitance, and $(W/L)_2$ is the ratio of channel width and length of T2. Because the resultant current is determined only by V_{DATA} and V_{REF} independently of threshold and supply voltages, the uniform current can be achieved.

$$\begin{aligned} I_{OLED} &= \frac{\beta}{2}\left(V_{DATA} + |V_{TH2}| - V_{REF} - |V_{TH2}|\right)^2 \\ &= \frac{\beta}{2}\left(V_{DATA} - V_{REF}\right)^2 \end{aligned} \quad (1)$$

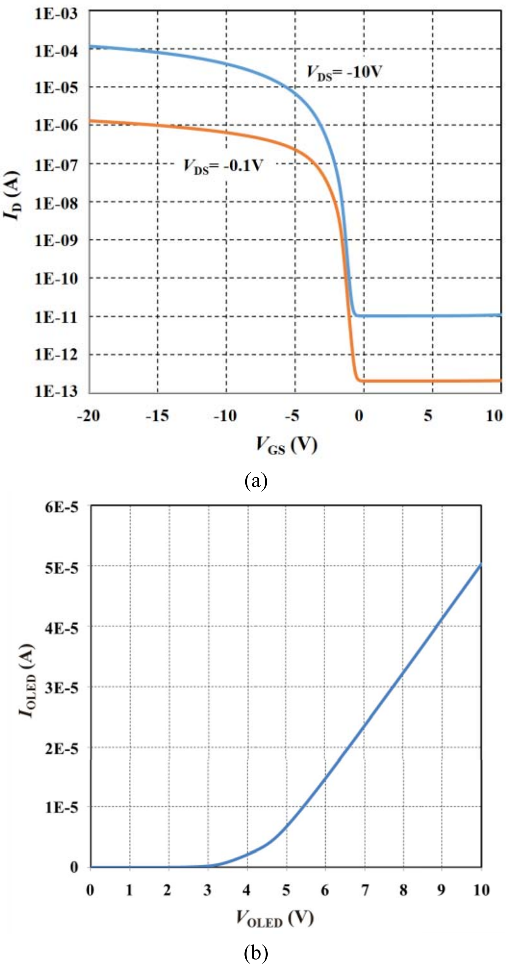

FIGURE 6. Device characteristics (a) transfer curve of TFT (W/L = 5 μm/7 μm) (b) characteristic curve of one OLED unit in an AC-OLED.

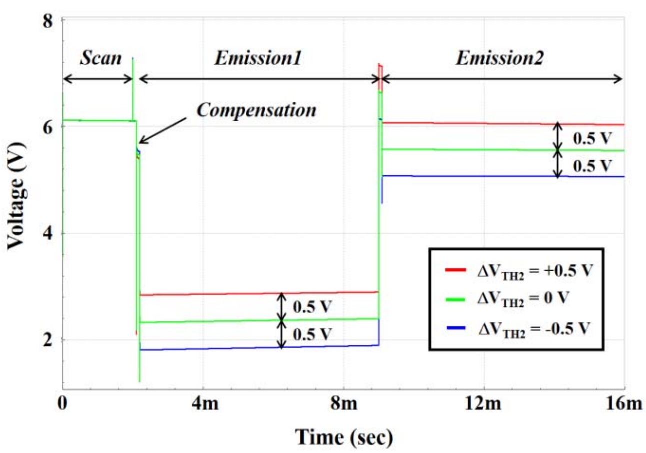

FIGURE 7. V_A waveforms regarding ±0.5 V variations on V_{TH2}.

4) *Emission2:* As illustrated in Fig. 5(d), because VS1 and VS2 are changed to VSS and VDD, drain and source nodes of T2 are also altered. To maintain source-gate voltage of T2 and I_{OLED}, the connection of C2 is modified by linking V_C to VS2 of VDD. Therefore, the current of the almost same amount as *Emission1* is provided to D2.

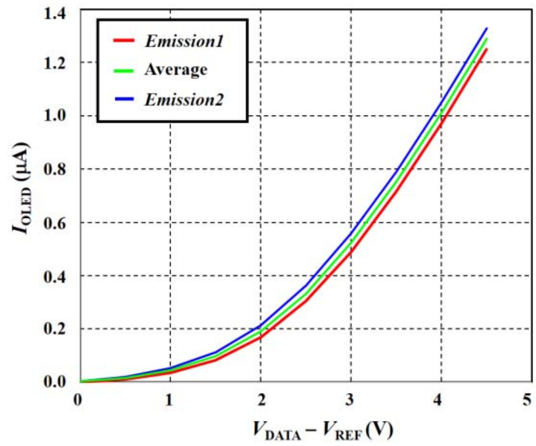

FIGURE 8. OLED current curves for emission periods of *Emission1* and *Emission2*.

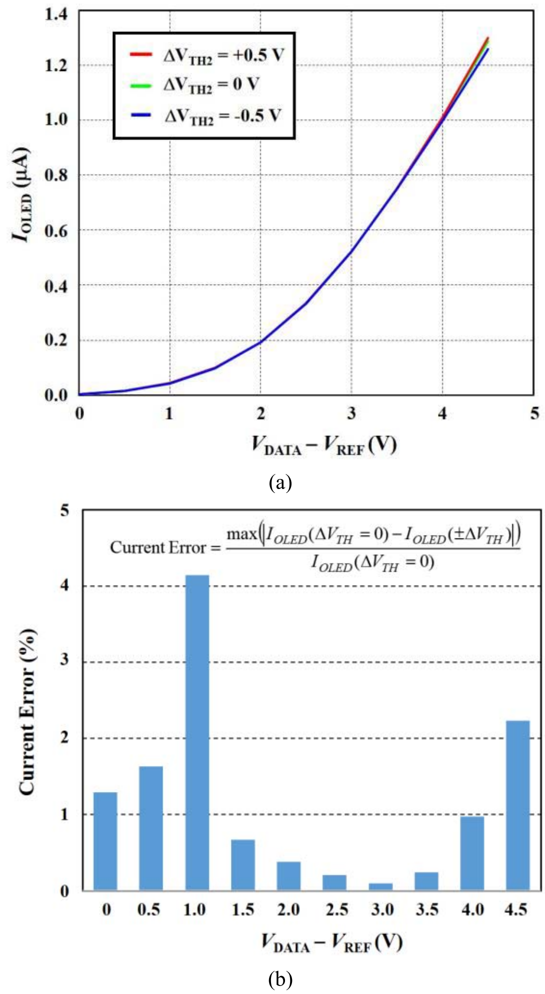

FIGURE 9. Current compensation performance for ΔV_{TH2} of ±0.5 V (a) current curves (b) current errors.

III. SIMULATION RESULTS

The SPICE simulation of a proposed pixel circuit is conducted with parameters of p-channel low temperature

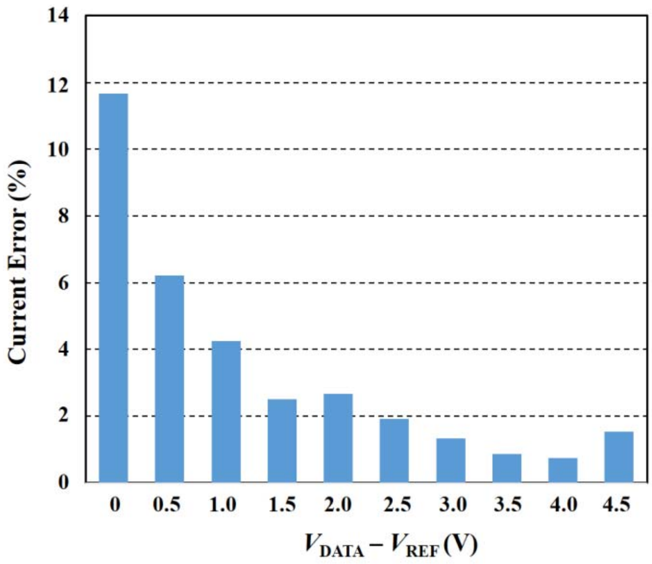

FIGURE 10. **Current errors for supply voltage variation of ±0.5 V.**

poly-silicon (LTPS) TFTs where mobility and threshold voltage are 31 cm^2/Vs and −1.7 V. The transfer curve for a switching TFT is plotted in Fig. 6(a) and the characteristic curve of an OLED is presented in Fig. 6(b).

The channel width and length of all switching TFTs are 5 μm and 7 μm. For a driving TFT T2, channel length and width are assigned as 35 μm and 6 μm. Two capacitors of C1 and C2 are set to 0.5 pF, and VDD and VSS for VS1 and VS2 are supplied at 10 V and 0 V, respectively. V_{REF} is provided by 3 V. The negative and positive voltages of other control signals such as SCAN[n], EN, and REF signals are −5 V and 10 V, respectively. The pulse width of SCAN[n] signals is 2 ms for a full-HD (1920 × 1080) display to be fully scanned for about 2 ms. The lengths of *Scan*, *Compensation*, *Emission1*, and *Emission2* are given as 2 ms, 200 μs, 6.9 ms, and 6.9 ms.

In the proposed circuit, the variations of V_{TH2} (ΔV_{TH2}) are compensated by V_A that is the gate voltage of T2 as plotted in Fig. 7. When V_{DATA} is 5 V and ΔV_{TH2} is ±0.5 V, V_A shows also the equivalent voltage difference of ±0.5 V for both *Emission1* and *Emission2* periods.

The currents at *Emission1* and *Emission2* as well as their average value are illustrated in Fig. 8 regarding the range of V_{DATA}–V_{REF} from 0 V to 4.5 V. In *Emission2*, V_A and V_C are pulled up toward VS2 of VDD by turning T6 on. Because V_C increases from V_D to VDD to start *Emission2* period, V_A is also pulled up by the capacitive coupling through C2. If the capacitor at V_A is only C2, the voltage change of V_A should be exactly equal to that of V_C. However, since there exist parasitic capacitors caused by T1, T2, T3, and T4, the change on V_A becomes smaller than that on V_C due to capacitor (C2) – capacitor (parasitic capacitors) division. Consequently, the gate-source voltage of T2 at *Emission2* is larger than at *Emission1* and the current at *Emission2* is higher than at *Emission1* as shown in Fig. 8. The average current curves and their current errors over ΔV_{TH2} are depicted in Fig. 9(a) and (b), respectively. Consequently, the threshold voltage variation is compensated with the lower current error than 5 % which is similar to the performance of a previous pixel circuit at ΔV_{TH} of ±0.3 V [26]. The average current error is estimated as 1.19 %. In addition, it is ensured that the AC-OLED pixel circuit can compensate the supply voltage variation of ±0.5 V with the average current error of 3.37 % as plotted in Fig. 10. The current error of 6 % at V_{DATA}-V_{REF} of 0.5 V is lower than 8 % of the previous one [26].

IV. CONCLUSION

The image-sticking issue has been a difficult and critical problem in AMOLED display applications for a long time. This paper addresses that issue with an AC-OLED that consists of two OLED units connected in opposite directions. The proposed SE pixel circuit programs the current once in the beginning of each frame, and then drives the AC-OLED in both ways for the remaining period of a frame time. Because one OLED unit emits the light for half frame time, the lifetime is extended substantially. Furthermore, the proposed circuit compensates threshold voltage and supply voltage variations. SPICE simulations with a p-channel LTPS TFT has verified that average current non-uniformities are reduced to 1.19 % and 3.37 % for threshold voltage and supply voltage variations of ±0.5 V, respectively.

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