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RESEARCH ARTICLE

Design of compensation pixel circuit with In-Zn-O thin film transistor for active-matrix organic light-emitting diode 3D display

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Abstract This paper presents a new compensation pixel circuit suitable for active-matrix organic light-emitting diode (AMOLED) stereoscopic three dimensional (3D) displays with shutter glasses. The simultaneous emission method was used to solve the crosstalk problem, in which the periods of initialization and threshold voltage detection occur for each pixel of whole panel simultaneously. Furthermore, there was no need of the periods of initialization and threshold voltage detection from the second frame beginning by employing threshold voltage one-time detection method. The non-uniformity of the proposed pixel circuit was considerably low with an average value of 8.6% measured from 20 discrete proposed pixel circuits integrated by In-Zn-O thin film transistors (IZO TFTs). It was shown that the OLED current almost remains constant for the number of frames up to 70 even the threshold voltage detection period only exists in the first frame.

Keywords active-matrix organic light-emitting diode (AMOLED), compensation pixel circuit, three dimensional (3D) display, simultaneous emission

1 Introduction

Active-matrix organic light-emitting diode (AMOLED) displays have gained more and more attention because of various advantages such as fast response time, light weight, wide viewing angle, low power consumption, and high brightness [1,2]. Recently, the AMOLED technology has been used to develop three dimensional (3D) displays, in which the distance and depth of image can be recognized like real objects [3–5]. Generally, 3D displays can be divided into two types: stereoscopic 3D displays with shutter glasses and autostereoscopic 3D displays without glasses. As seen from Fig. 1(a), the refresh frame rate of at least 120 Hz is required for stereoscopic 3D displays with special glasses. The left shutter glass is on when playing the left image, and the right shutter glass is on when playing the right image. However, this may cause a serious crosstalk problem which is undesirable in 3D displays. Frame rate of 240 Hz is used to restrain the crosstalk problem, in which a black image is inserted between the left and the right images as shown in Fig. 1(b). However, there is still considerable crosstalk since the switching time of the liquid crystal (LC) based shutter glasses is several milliseconds. As shown in Fig. 1(c), the crosstalk problem can be completely avoided at the frame rate of 480 Hz for the progressive emission method [3]. Note that, as shown in Fig. 1(d), the simultaneous emission method can avoid the crosstalk problem at only 120 Hz frame rate because the time for the periods of data input can be used to switch the shutter glass since there is no light emitting for the above three periods [4–6].

For the pixel circuit, the conventional two-thin film transistors (TFTs) one-capacitor (2T1C) pixel circuit is not suitable for AMOLED displays because the OLED current is non-uniform due to the variations in the threshold voltage of the driving TFT [7,8]. Several voltage programmed pixel circuits have been developed to compensate the threshold voltage shift of the driving TFT for enhancing the brightness uniformity of AMOLED displays [7–9]. Generally, the operational scheme of compensation pixel circuit can be divided into four stages: initialization period, threshold voltage detection period, data input period and emission period. For the compensation pixel circuit employing simultaneous emission method, the periods of initialization and threshold voltage

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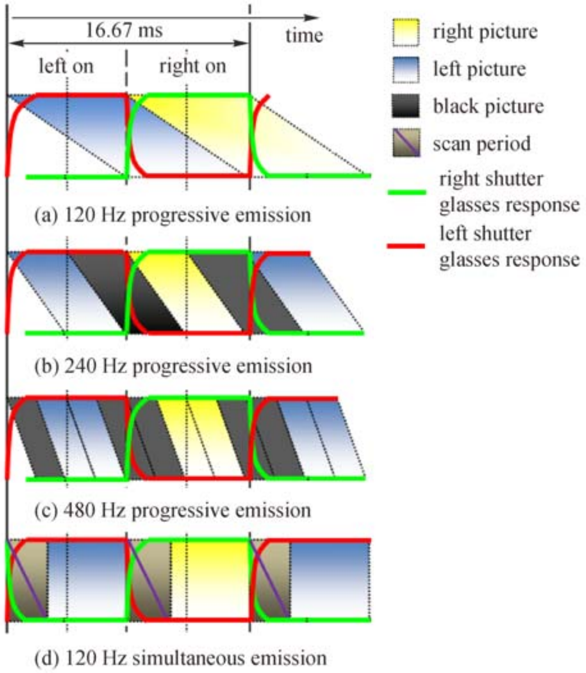


(a) 120 Hz progressive emission

(b) 240 Hz progressive emission

(c) 480 Hz progressive emission

(d) 120 Hz simultaneous emission

Fig. 1 3D implementation by the conventional progressive emission at (a) 120 Hz; (b) 240 Hz; and (c) 480 Hz, respectively, and (d) by the simultaneous emission at 120 Hz

detection simultaneously occur for each pixel of whole panel. And then data voltage is input line by line. Afterwards, the OLED emits light at the same time. Lee et al. proposed pixel circuit for 3D display employing simultaneous emission method [5]. However, it needs a programmed power supply which makes peripheral driving circuits of AMOLED displays be complicated. Wu et al. developed the threshold voltage one-time detection method for AMOLED displays, in which the periods of initialization and threshold voltage detection are needless from the second frame beginning [10]. However, there were only simulation results and the emission time is different among the different lines [11]. In this paper, we applied the threshold voltage one-time detection method in AMOLED 3D display driven with the simultaneous emission method. And we also presented a new compensation pixel circuit for the driving method, which is verified by both the simulation results and the experimental measurements.

2 Proposed pixel circuit operation

Figure 2 shows the proposed pixel circuit and its driving scheme. This pixel circuit is composed of one driving TFT (T4), three switching TFTs (T1, T2, and T3), and two storage capacitors (C1 and C2). V_{data} is the data voltage signal, V1 is the line scan signal which is used to control T1, V2 and V3 are the control signals for whole panel. The operational scheme for the first frame is described as follows.

1) Initialization period. V1 of whole panel, V2 and V3 are set to high level to turn on all the switching TFTs, V_{data} is set to 0 V. The voltage at node C is pulled down to 0 V through T1. And the voltage at node A is set to a high level, which is larger than the threshold voltage of T4. Note that, there is certain current passing through OLED during this period. However, the period is short enough and it only occurs one time every several decades frames when applying the threshold voltage one-time detection method as seen below. As a result, this current may hardly affect the contrast ratio of AMOLED display. In addition, the OLED current can also be avoided by introducing an additional initialization branch circuit in the compensation pixel circuit [3].

2) Threshold-voltage detection period. V2 and V1 remain high, V3 is set to low voltage to turn off T3. The voltage at node A is discharged through T2 and T4 until T4 is turned off. At the end of this period, the threshold-voltage (V_{th}) of the driving TFT (T4) is stored at C1, i.e., $V_{\mathrm{A}} = V_{\mathrm{th}}$ and $V_{\mathrm{C}} = 0$. Note that, the threshold voltage of T4 for all pixels of panel is simultaneously detected in this period.

3) Data input period. V2 and V3 are set to low voltage to turn off T2 and T3. The data of each line are loaded by turning on T1 line by line. V_{A} changes to be V_{th} +

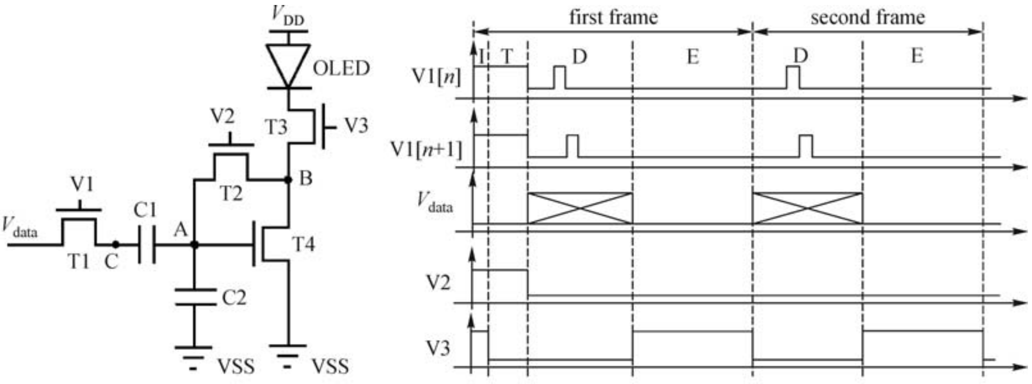


Fig. 2 Proposed pixel circuit schematic and control signals timing diagram of the first and second frames

C1*V_{data}/(C1 + C2) from V_{th} due to the capacitor coupling effect between C1 and C2.

4) Emission period. V3 goes to high voltage to turn on T3, and V1 and V2 go to low voltage to turn off T1 and T2 respectively. Note that, OLED in the whole panel emits simultaneously in this period. The OLED current is equal to the drain current of T4, which is working in the saturation region. Then, we have

$$\begin{aligned} I_{\text{OLED}} &= \beta(V_{\text{gs}} - V_{\text{th}})^2 \\ &= \beta(V_{\text{A}} - V_{\text{th}})^2 \\ &= \beta\left(\frac{\text{C1}}{\text{C1} + \text{C2}} V_{\text{data}}\right)^2, \end{aligned} \tag{1}$$

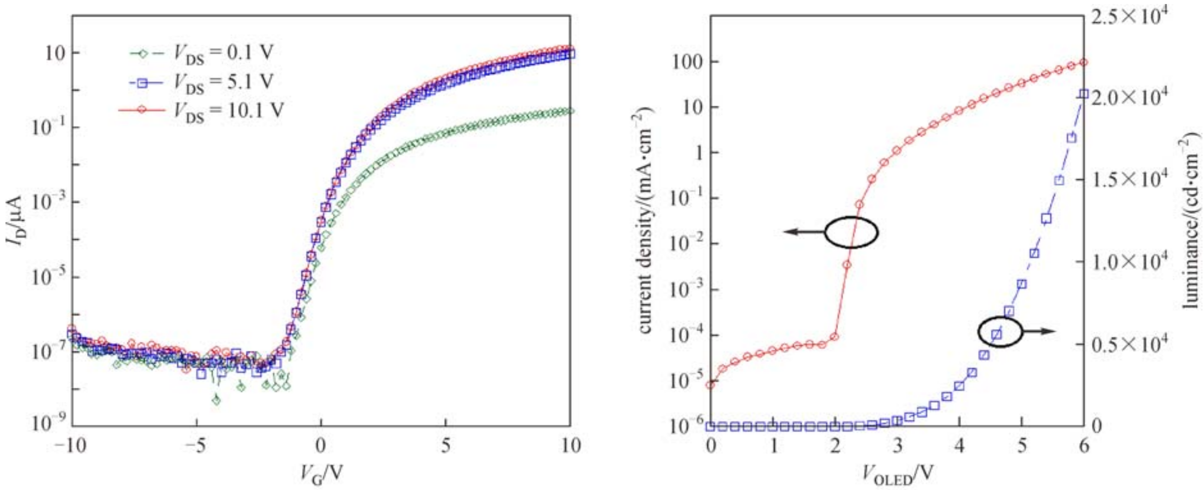
with $\beta = 0.5\mu C_{\text{ox}} W/L$, where W, L, μ, and C_{ox} are the channel width, the channel length, the field-effect mobility, and the gate oxide capacitance per unit area, respectively. As seen from Eq. (1), uniform brightness image performance can be achieved since the OLED current is independent of the threshold voltage of driving TFT (T4) and OLED.

In principle, there is no need of the periods of initialization and threshold voltage detection from the second frame beginning by employing threshold voltage one-time detection method [9]. However, the threshold voltage of T4 should be detected again after a few frames due to the leakage current of T2. Anyway, the driving method of the proposed pixel circuits is similar to that of conventional 2T1C pixel circuit or TFT LCD.

3 Result and discussion

Figure 3 (a) shows the characteristics of IZO TFTs, the fabrication process of which can be seen in Ref. [12]. It is shown that the mobility and threshold voltage are 13.3 cm^2/(V·s) and 0.3 V, respectively. Note that, the TFTs have excellent turn-off performance with the leakage current as about 50 fA. The OLED device structure is ITO(170 nm)/MeO-TBD:F4-TCNQ(150 nm, 4 wt%)/NPB(20 nm)/Bebq2(30 nm)/LiF(1 nm)/Al(200 nm), which emits red light. The characteristics of OLED are shown in Fig. 3(b). The current efficiency η = 21 cd/A and its area is 4900 μm^2. The W/L of the driving TFT (T4) is designed as 20 μm /10 μm based on the characteristics of TFTs and OLED to make the target luminance of OLED up to 800 cd/cm^2. T1, T2 and T3 are the common switching TFTs, the W/L of which is chosen as 10 μm/10 μm. The capacitance of C1 and C2 can be set as a small value to ensure timely charging in the data input period since the leakage current of TFTs is low enough, such as 0.4 pF. The value of V_{DD} should be large enough to make the driving TFT (T4) working at the saturation region in the whole range of data voltage. The high/low voltage of control signals (V1, V2, V3) is set to turn on/off TFT completely. The design parameters of the proposed pixel circuit are all indicated in Table 1.

The circuit simulation was performed by SMART-SPICE software to confirm the effectiveness of the proposed pixel circuit by fitting the characteristics of TFTs and OLED. In simulation, OLED was replaced by a diode-connected TFT in parallel with a capacitor, of which the threshold voltage was set to be 3.3 V corresponding to the characteristics of OLED. Figure 4 shows the transient simulation results of the voltage at node A (V_{A}) and the OLED current for inputting same data voltage (3 V) with three different threshold voltage (0.2 V, 0.6 V, 1.0 V) of T4 at the first frame. It was shown that the threshold voltage of the driving TFT T4 was successfully detected in period (2) at the above three conditions, and OLED current was almost same with maximum difference as 15.3 nA in period (4). Consequently, the proposed pixel circuit can



(a) (b)

Fig. 3 Characteristics of (a) IZO TFT (W/L = 20 μm/10 μm) and (b) OLED

Table 1 Design parameters of the proposed pixel circuit

parameter	value
V1, V2, V3/V	– 5~12
V_{DD}/V	15
(W/L)T1, T2, T3/(μm·μm^{-1})	10/10
(W/L)T4/(μm·μm^{-1})	20/10
C1/pF	0.4
C2/pF	0.4

effectively compensate for the threshold voltage shift of the driving TFT. And the proposed pixel circuit may be suitable for 3D displays application since there is no OLED current during the periods of (2) and (3). Note that, the input data time was 5 μs in this simulation, so it can be adapt to the WXGA (1280×720) displays. Actually, this input data time may be further shortened for application in the higher resolution display such as FHD (1920×1080).

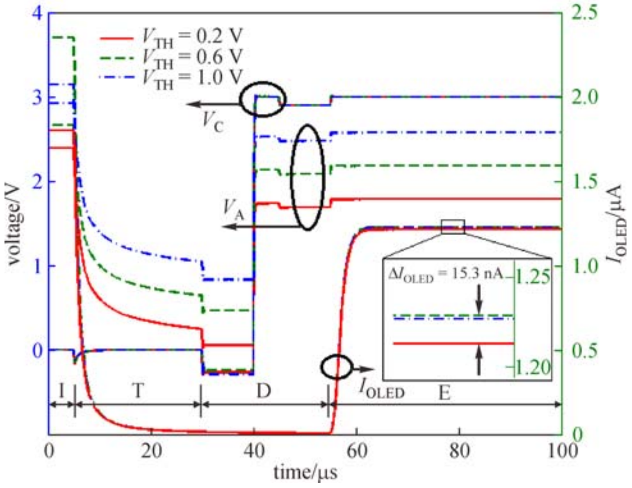


Fig. 4 Transient simulation results of the node voltage and OLED current

Figure 5 shows the micrograph of the proposed pixel circuit, of which the parameters are indicated in Table 1. Figure 6 shows the measured non-uniformity of OLED current versus the average current through those 20 discrete proposed pixel circuit, as well as that of the conventional 2T1C pixel circuit with the same amount. It was shown that the non-uniformity of the proposed pixel circuit was significantly reduced with an average value of 8.6% compared with that of the conventional 2T1C pixel circuit with an average value of 41.4%. Obviously, our proposed pixel circuit can effectively compensate for the threshold voltage shift of the driving TFT. However, there still exists a certain value of the OLED current non-uniformity for the proposed pixel circuit, which may be caused by the non-uniformity of the mobility for the driving TFT. It is well known that the OLED current is linear with the mobility of the driving TFT, whereas the mobility non-uniformity of the driving TFT cannot be compensated in the proposed pixel circuit. As a result, the TFTs' process should be further optimized to raise the mobility uniformity of TFTs.

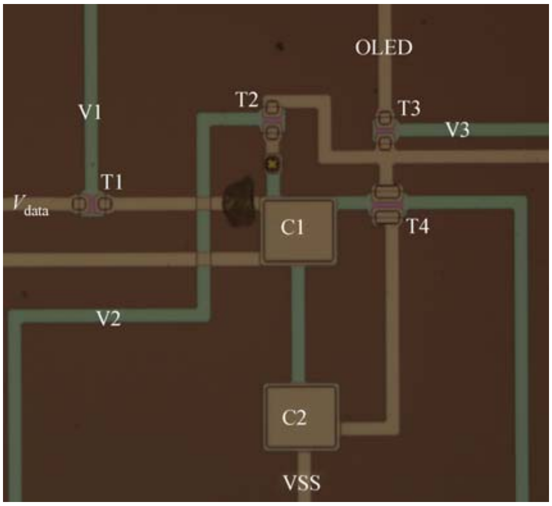


Fig. 5 Optical images of the proposed pixel circuit

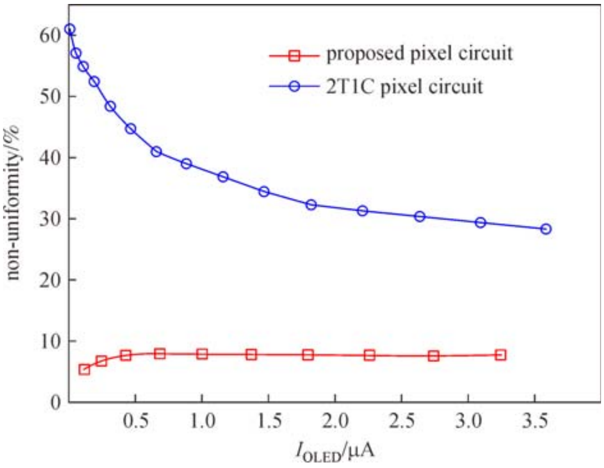


Fig. 6 Non-uniformity of OLED current versus average current for the proposed pixel circuit and conventional 2T1C pixel circuit

Figure 7 shows the measured OLED current versus the data voltage with different V_{DD}. It was shown that the OLED current was almost independent of the power voltage V_{DD}, and only affected by the data voltage. As a result, the proposed pixel circuit has a good immunity to the IR voltage-drop in the power line. That is mainly because the IR voltage-drop in the power line (V_{DD}) for the pixel circuits with N-type TFTs may not affect the OLED current as long as the driving TFT works in the saturation region. As seen in Fig. 7, the OLED current at the condition of V_{DD} = 11 V deviates a little from those at the

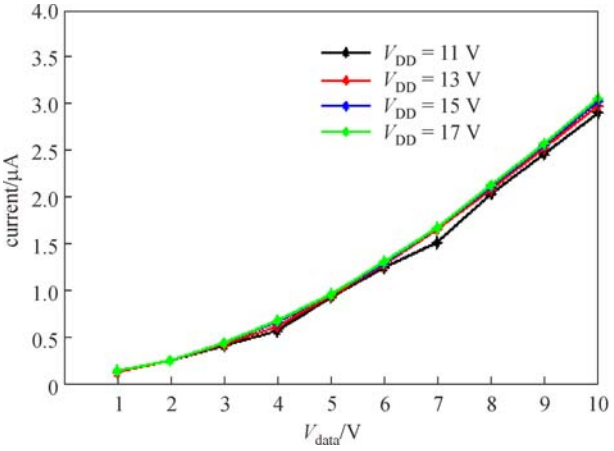


Fig. 7 OLED current versus input data at different power voltage V_{DD}

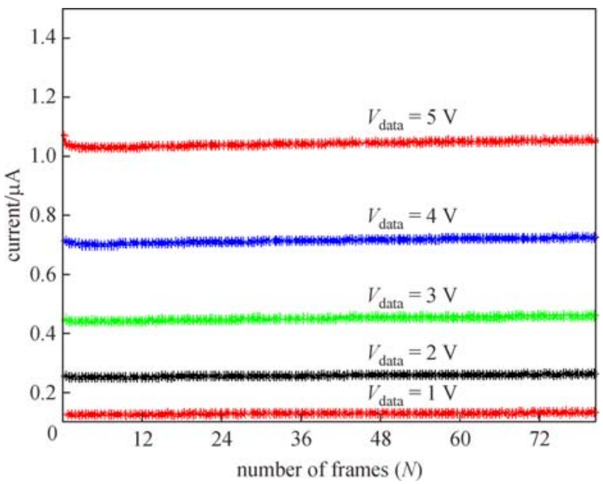


Fig. 8 Measured OLED current versus N at different input data

other three conditions. The reason may be that the driving TFT (T4) works in the linear region instead of the saturation region for a relatively small value of V_{DD}.

Figure 8 shows the measured OLED current versus number of frames (N) with different input data voltage (1 V, 2 V, 3 V, 4 V and 5 V) at 120 Hz frame frequency. Note that, the threshold voltage detection period only exists in the first frame. Then, from this moment beginning, the effect of the leakage current of T2 on V_{A} should be taken into account. The variation of V_{A} due to the leakage current of T2 (I_{Leak}, which is linear with the width of TFTs) can be expressed as

$$\Delta V_{\mathrm{A}} = \frac{\frac{N}{f} \times I_{\mathrm{Leak}}}{\mathrm{C1} + \mathrm{C2}}, \tag{2}$$

where f is the frame frequency, here it is 120 Hz. Note that, it is normally required that the variation of V_{A} due to the leakage current effect should not exceed the minimum difference ($\Delta V_{\mathrm{A\_MIN}}$) between neighboring gray voltages. It is shown that the OLED current almost remains constant even if N is up to 70. Substituting the conditions of $\mathrm{C1} = \mathrm{C2} = 0.4$ pf, $N = 70$, $f = 120$ Hz and $I_{\mathrm{Leak}} = 25$ fA into (2), ΔV_{A} is calculated as 18 mV, which may still be an acceptable value.

4 Conclusion

This paper presents a new compensation pixel circuit suitable for AMOLED stereoscopic 3D displays by the simultaneous emission method. It was measured that the non-uniformity of the proposed pixel circuit was considerably low with an average value of 8.6%. Moreover, employing threshold voltage one-time detection method, there was no need of the periods of initialization and threshold voltage detection from the second frame beginning. It was shown that the OLED current almost remains constant even if the number of frames was up to 70.

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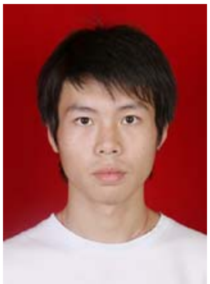

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