New Pixel Driving Circuit for Active-Matrix OLED-on-Silicon *

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Abstract: A new pixel driving circuit for active-matrix OLED (Organic Light Emitting Diode) on silicon with three transistors is proposed. The circuit can solve the problem that traditional MOS current operating in the saturation region simply cannot handle very small OLED pixel currents (smaller than 1 μA) given the pixel areas. With software of H-spice, this new circuit and the conventional two-transistor pixel driving circuit are simulated and compared. Simulation results show that this new proposed circuit is more suitable for OLED-on-silicon to realize multiple gray levels.

Key words: active-matrix OLED-on-silicon; pixel driving circuit; gray scale
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一种新的有源硅基OLED象素驱动电路 *

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摘 要:提出了一种新的有源硅基有机发光二极管(OLED-on-Silicon)象素驱动电路.该电路解决了具有特定象素大小的OLED的极小象素电流(小于1 μA)与传统MOS器件大的饱和驱动电流之间的不匹配问题.利用Synopsys公司的仿真软件H-spice,对该电路和传统的两管象素驱动电路进行了模拟,结果表明该电路作为OLED-on-Silicon的象素驱动更容易实现多级灰度.

关键词:有源硅基OLED驱动;象素驱动电路;灰度等级
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The OLED-on-silicon (Organic Light Emitting Diode on silicon) is a developing micro-display technology. It integrates OLED devices with mature and inexpensive CMOS driving ICs and has already attracted much attention. Because of the superior performances of OLED, such as fast response, large view angle and low power consumption, this micro-display technology is promising.

OLED is a self-luminescence device. Its brightness is controlled by the current density. The typical brightness-voltage-current (BVI) curve[1] of OLED is showed in fig. 1. For OLED pixels with an area of less than 1000 μm^2 working on a voltage of 10V, the pixel current will not exceed 1.2 μA. This pixel current is not comparable with the large state-on current of traditional CMOS device. When traditional CMOS device drives OLED directly, driving current cannot change with gate voltage any more. To realize gray scale, very small width-to-length ratio CMOS device is needed. The device size will be too large to fit in micro-display pixel area.

In literature[2], CMOS devices sub-threshold current was used to drive OLED. It's a good strategy for OLED-on-silicon. But the pixel driving circuit's complexity increases. Five transistors and

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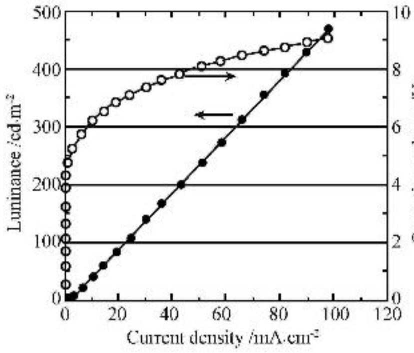


Fig. 1 BVI curve of OLED pixels [1]

two control signals are needed. Pixel circuit layout size increases greatly. It's not practical to implement this circuit with submicron CMOS process technologies for micro-display.

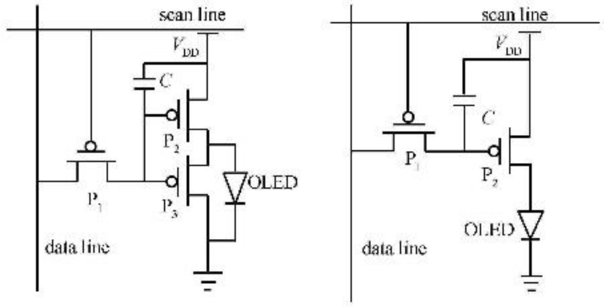
In this paper, a new three-transistor pixel driving circuit is proposed, which uses two transistors in series to supply OLED with needed voltage. OLED is paralleled to one of those two transistors, and is not driven by CMOS device directly. The large driving current of CMOS device is no longer a problem. Gray scale can be easily realized by this driving circuit.

1 The Proposed Three-Transistor Pixel Driving Circuit

Fig. 2 (a) shows the proposed pixel circuit. There are three transistors, a capacitor, a data line and a scan line. Compared with conventional two-transistor pixel circuit[3] in fig. 2 (b), only one transistor P_3 is added. P_1 is still the pass-transistor, controlled by signal on scan line. P_2 is in series with P_3 and their gates are connected together. C is the storage capacitor. OLED is paralleled to P3, and isn't driven by P_2 completely. The difference of P_2 and P_3 currents drives OLED. That's the main difference of these two pixel circuits.

For circuit in fig. 2 (a), when P_2 turns on, OLED will turn on too, the voltage on OLED will be V_{DD} first, and then P_3 turns on and circuit becomes stable. So there is that:

$$V_{S(P_3)}(=V_{OLED}=V_{D(P_2)}) > V_{G(P_3)}(=V_{G(P_2)}) + V_{TH} ==> V_{SD(P_2)}(=V_{DD}-V_{D(P2)}) < V_{SG(P2)}(=V_{DD}-V_{G(P2)}) - V_{TH}$$



(a) The proposed three-transistor pixel driving circuit;
(b) Conventional two-transistor pixel driving circuit
Fig. 2

P_2 is working in linear region. And it's also obvious that:

$$V_{SD(P3)}(=V_{S(P3)}-0) > V_{SG(P3)}(=V_{S(P3)}-V_{G(P_3)}) - V_{TH}$$

P_3 is working in saturation region. Here, V_S, V_G, V_D, V_{SD}, and V_{SG} with a subscript '(P_2)' or '(P_3)' represent the voltage on P_2 or P_3 electrode of source, gate, drain, source-drain, and source-gate respectively. V_{OLED} means the voltage on OLED, and V_{TH} is the absolute value of transistors' threshold voltage. With the working region of P_2 and P_3 obtained above, there is that:

$$I_{P_2} = k\left(\frac{W}{L}\right)_{P_2} 2\left(V_{DD} - V_{G(P_2)} - V_{TH} - \frac{1}{2}(V_{DD} - V_{D(P_2)})\right)(V_{DD} - V_{D(P_2)}) \quad (1)$$

$$I_{P_3} = k\left(\frac{W}{L}\right)_{P_3} (V_{S(P_3)} - V_{G(P_3)} - V_{TH})^2 \quad (2)$$

Where, $k = 1/2\,\mu_p C_{OX}$, and μ_p is the hole mobility, C_{OX} is the gate oxide capacitance per unit area. And (W/L) with a subscript 'P_2' or 'P_3' represents width-to-length ratio of P_2 or P_3. With OLED working current neglected, there is that $I_{P_2} = I_{P_3}$, and with $V_{S(P_3)}(=V_{OLED}=V_{D(P_2)}) > V_{G(P_3)}(=V_{G(P_2)}) + V_{TH}$, solving equation group (1) and (2), we get that:

$$V_{OLED} = V_G\left(1 - \sqrt{\left(\frac{W}{L}\right)_{P_2} / \left[\left(\frac{W}{L}\right)_{P_2} + \left(\frac{W}{L}\right)_{P_3}\right]}\right) + V_{TH} + (V_{DD} - V_{TH})\sqrt{\left(\frac{W}{L}\right)_{P_2} / \left[\left(\frac{W}{L}\right)_{P_2} + \left(\frac{W}{L}\right)_{P_3}\right]} \quad (3)$$

V_{OLED} has a linear relationship with V_G (gate voltage of P_2 and P_3).

If $V_{DD} = 10$ V, $V_{TH} = 2$ V, and considering the low voltage loss of P-type pass-transistor and that P_2 and P_3 must be on, V_G will vary from 2 V to 8 V. S:

$$6 \times \left(\frac{W}{L}\right)_{P_2} / \left[\left(\frac{W}{L}\right)_{P_2} + \left(\frac{W}{L}\right)_{P_3}\right] + 4 < V_{OLED} < 10\ \text{V} \quad (4)$$

It is right in the voltage range when OLED turns on. The width-to-length ratios of P_2 and P_3 determine the OLED working range. To increase this working range we can decrease $(W/L)_{P_2}$ and increase $(W/L)_{P_3}$. So small $(W/L)_{P_2}$ and large $(W/L)_{P_3}$ will be chosen. And the working range can be properly adjusted according to the number of gray levels.

In fig. 1, there is a quasi-linearity relationship of current density and voltage (V_{OLED}) when OLED turns on. And the brightness of OLED is proportional to OLED current density. So a quasi-linearity gray scale can be realized by this three-transistor pixel driving circuit.

2　Circuit Simulation with H-spice

To simulate the pixel circuit, OLED model for H-spice are needed. Here, the model[4] in fig. 3 (a) is used. A series resistor R connects with a diode D paralleled to a capacitor C. And the OLED model:

$$I_{OLED} = I_s\left(e^{\frac{V_{OLED}-IR}{nV_T}} - 1\right) \quad (5)$$

is based on conventional diode exponential model, where I_s is reverse saturation current, n is non-ideality factor, V_T is thermal voltage and R is the series resistor. Based on BVI curve of OLED in fig. 1, parameters in formula (5) are obtained. For OLED pixel with an area of 30 ×30 μm there is that:

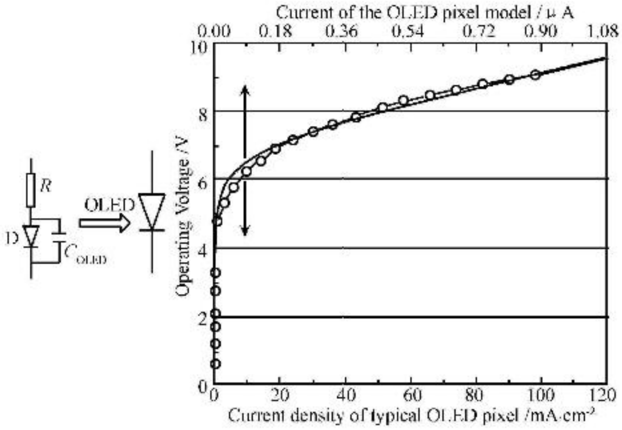
$I_s = 5$ pF, $n = 25.5$, $R = (V_{OLED}/8) \times (V_{OLED}/10)^{1/2} \times 1.2$ MΩ,

$C_{OLED} = 30 \times 30\ \mu m^2 \times 25\ nF/cm^2$ [5] $= 0.225$ pF

The high value of n and R shows that this model has no physical background. Its applicability is limited.

Fig. 3 (b) shows the V-I curve of this model, which basically fits with the typical OLED V-I curve when operating voltage is smaller than 10 V. So this OLED pixel model is suitable to be used in OLED driving circuit simulation with working voltage $V_{DD} = 10$ V. The current range of OLED pixels is determined by the OLED pixel current density range and the OLED pixel area, 1.08 μA = 120 mA/cm^2 ×30 μm ×30 μm.

In H-spice simulation, the MOSFET model



(a) OLED model for H-spice simulation; (b) Comparison of V-I curve of OLED model and typical OLED

Fig. 3

level 49 was chosen and an assumption that PMOSFETs will work normally on voltage of 10 V was made. For a QVGA (320 ×240) display operating at 60 frame/s, the row scanning frequency is 14.4 kHz. Here, a scan signal with frequency of 20 kHz was used. With C = 3 pF, $(W/L)_{P_1} = 1.6/0.8$, $(W/L)_{P_2} = 1.6/0.8$, 1.6/2.4, and 1.6/5, $(W/L)_{P_3} = 10/0.8$, and a 16 levels step signal on data line, the three-transistor pixel circuit was simulated, and results are showed in fig. 4. Because of MOS device threshold voltage, signals have a valid working range. Voltage levels in range of 2～8 V, can drive OLED to light. In the valid working range, all gray levels are realized. And the gray levels have quasi-linearity. It's clear that the voltage range of OLED increased with the decrease of $(W/L)_{P_2}$. It accords with the conclusion obtained in part 2.

Two-transistor pixel driver was also simulated with the same input signals, the same value of C and $(W/L)_{P_1}$. Results are still showed in fig. 4. When $(W/L)_{P_2} = 1.6/0.8$, the OLED current has only two levels. Only two gray levels (black and white) can be realized. When $(W/L)_{P_2}$ becomes smaller, the realized gray levels increase. Fig. 4 shows the OLED current when $(W/L)_{P_2} = 1.6/50$, 1.6/100, 1.6/200. With the decrease of $(W/L)_{P_2}$, the non-linearity of gray levels becomes inconspicuous gradually. But the cost is the great increase of P_2 size. So two-transistor pixel circuit is difficult to realize multiple gray levels and is not suitable for OLED micro-display implemented on silicon.

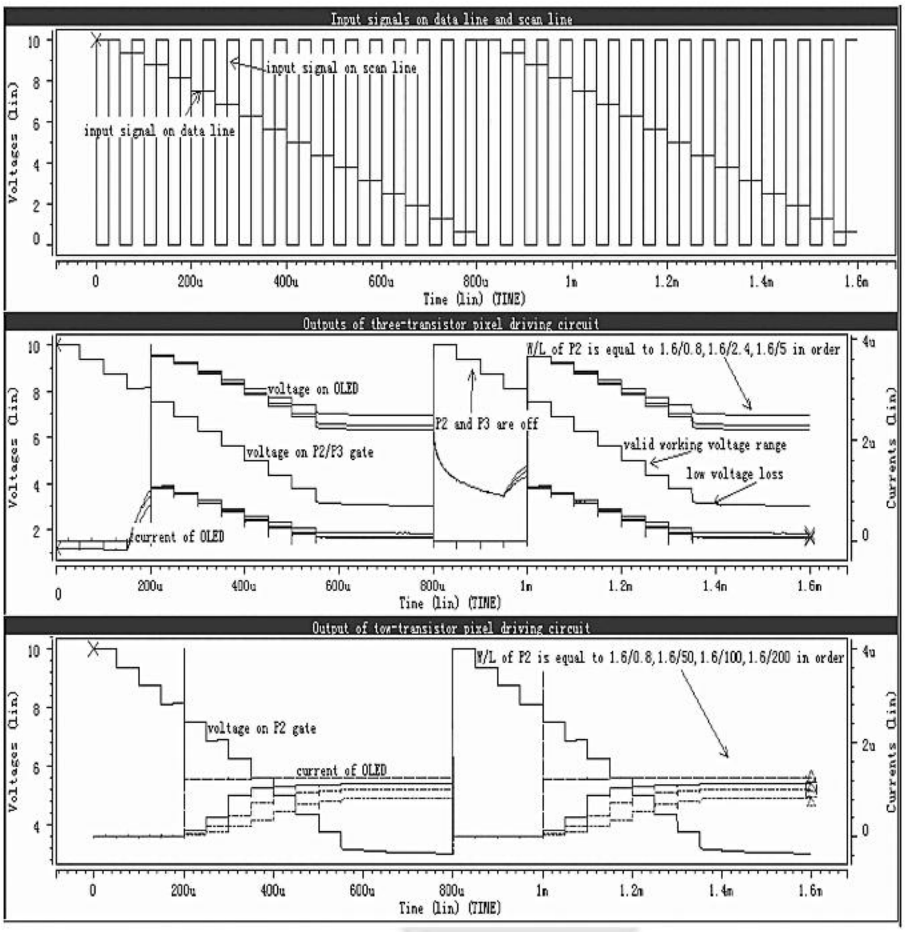


Fig. 4 Simulation results of the three-transistor and two-transistor pixel driving circuits

So, the proposed three-transistor pixel driving circuit is a better choice than the conventional two-transistor pixel driving circuit for OLED-on-silicon micro-display. Though one more transistors are needed, its pixel layout size is still smaller than that of conventional pixel circuit when multiple gray levels are needed.

3 Conclusions

A new pixel driving circuit for active-matrix OLED-on-silicon with three transistors and a capacitor was proposed. Compared with conventional two-transistor pixel driving circuit, this circuit is more suitable for OLED-on-silicon to realize multiple gray levels. It can successfully realize quasi-linearity gray scale. And it is also simpler than the pixel circuit which uses sub-threshold current of MOS devices to drive OLED.

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