A new OLED SPICE model for pixel circuit simulation in OLED-on-silicon microdisplay design*

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Abstract: A new equivalent circuit model of organic-light-emitting-diode (OLED) is proposed. As the single-diode model is able to approximate OLED behavior as well as the multiple-diode model, the new model will be built based on it. In order to make sure that the experimental and simulated data are in good agreement, the constant resistor is exchanged for an exponential resistor in the new model. Compared with the measured data and the results of the other two OLED SPICE models, the simulated I–V characteristics of the new model match the measured data much better. This new model can be directly incorporated into an SPICE circuit simulator and presents good accuracy over the whole operating voltage.

Key words: OLED-on-silicon; pixel circuit; microdisplay; SPICE model; CMOS
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1. Introduction

OLEDs have advantages of a wide viewing angle, fast response time, high brightness, high contrast, high luminous efficiency, and low power[1,2]. The CMOS (complementary metal–oxide–semiconductor) is a very mature and economic semiconductor fabrication technology. Building the OLED on silicon combines the advantages of OLED and CMOS, and we call this technology OLEDoS (organic-light-emitting-diode-on-silicon). OLEDoS is ideally suited to microdisplay applications such as viewfinders, head-mounted displays, wearable computers, digital cameras and other portable devices[3,4].

In order to predict the operating current of an OLED in the driving circuit design phase, we should develop an OLED model for simulation. As is known, SPICE models are used by circuit and systems engineers in the design of commercial products and are also useful for the interpretation of empirical electrical device characterization trends. For this reason, we construct an OLED SPICE model by using Accelicon model builder program (MBP) software. The establishment of the SPICE model is based on the experimental data, so first, a large area (current will be large so it is convenient for test instruments) of OLED will be grown on a silicon chip. Then, testing voltage is added between the anode and cathode of the OLED and we can get the current density and luminance of the OLED. For the reason that the area of an OLED pixel cell is generally less than 300 μm^2 (even somewhat smaller), the pixel working current should be modulated between hundreds of picoamperes (pA) and tens of nanoamperes (nA). In this paper, we employ a subthreshold-voltage-scaling OLED pixel driver topology[4] to test the accuracy of the OLED SPICE model.

2. Characteristics of the OLED device

As shown in Fig. 1, each OLED device consists of a glass substrate coated with a transparent indium-tin-oxide (ITO) anode, on which a hole injection layer (HIL), a hole transport layer (HTL), and an electron transport layer (ETL) are vapor-deposited; the top layer is a Ag cathode (electron injection layer, EIL)[5]. The thickness of each layer is about tens of nanometers and the total thickness of the OLED will be 100 nm

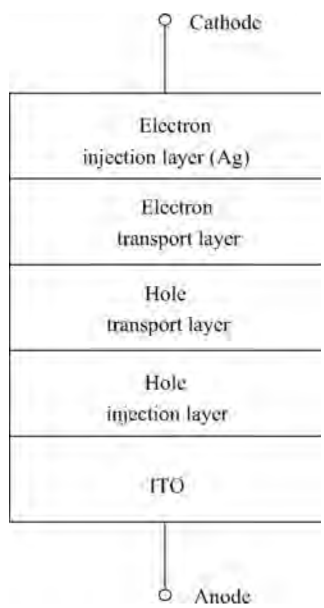

Fig. 1. A cross section of the OLED.

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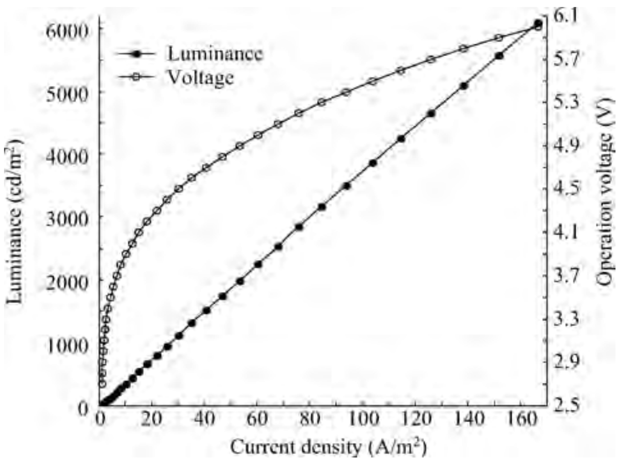


Fig. 2. OLED current density versus luminance and voltage characteristic.

approximately. When a voltage is added, which makes sure that a current is passed through the device, bright green or white emission is obtained.

Figure 2 shows the current density versus luminance and voltage characteristic. The brightness is directly proportional to the current density flowing through the OLED device. The I/V characteristic curve shows that current starts to flow at about 2.9–3.1 V and follows the power-law dependence of the current on voltage from 2.9 to 6 V. Assuming that the threshold voltage of the OLED device is 3 V and a pixel cell circuit area is 14.5 × 14.5 μm^2, the lowest grayscale current will be:

$$I_{\min} = 1.5431\,\text{A/m}^2 \times 14.5\,\mu\text{m} \times 14.5\,\mu\text{m} = 324.4\,\text{pA}. \quad (1)$$

That is to say the pixel working current can be as low as 324 pA.

3. Developing the OLED SPICE model

In the original OLED model assumption, each individual layer (Fig. 1) is modeled as a capacitor C shunted by a series combination of a resistor R_1 and a diode D, as shown in Fig. 3. The capacitor C represents the physical capacitance of the layer; large series resistances R_1 are an inevitable consequence of employing materials with extremely low mobility; the resistor R_2 accounts for the relatively large bulk series resistance associated with an OLED layer; the diode D accounts for the rectifying nature of an individual OLED layer. An additional resistor is placed in series with the stack of modeled layers to account for the sheet resistance of the ITO anode and any external resistance[5].

However, it is complex to fit the multiple-diode SPICE model to measured data and some convergence problems in the SPICE DC or transient analysis may be encountered. Consequently, a double-diode paralleled model (Fig. 4(a)) has been presented in Ref. [6], in which two diodes represent the OLED I–V relationship at low and high V_{OLED}, respectively. Unfortunately, errors between simulated current and measured current reached nearly 8% at high V_{OLED} in the double-diode paralleled model, which will be inconvenient when we want to control the highest OLED brightness. As shown in Fig. 4(b), Reference [7] introduced a physical-based OLED model which considered the effect of high built-in voltage existing between the organic materials and the non-ideal ohmic effect occurring at the contact between metal and organic material. Nevertheless, it encountered accuracy issues when the OLED begun to turn on.

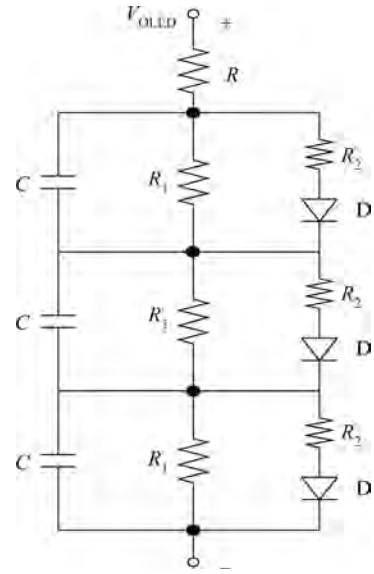


Fig. 3. Multiple-diode SPICE model for an OLED.

Actually, according to Ref. [5], a simpler model is also able to approximate OLED behavior as well as the multiple-diode model and References [2, 8, 9] adopt a simpler OLED model when simulating the pixel circuit. In addition, the transient characteristics of the OLED do not influence the working of the pixel circuit much in this paper. Therefore a series resistance R_2 and a capacitor C in parallel with a resistance R_1 and a diode which is in series with a resistor R_s make up the simpler OLED model, as shown in Fig. 4(c). Now, the diode D stands for the total rectified current flow in OLED, the capacitor C is the total stack capacitance, the shunt resistor represents the total bulk resistance of OLED layers and the resistor still accounts for the ITO sheet resistance. So, we will make some modifications based on this single-diode OLED model to predict precisely the working current of an OLED in the circuit design phase.

In Fig. 4, diode D current calculation equation:

$$I = I_S \left(\exp \frac{V}{nV_T} - 1 \right), \quad (2)$$

where I_S is reverse saturation current or leakage current; n is an empirical constant between 1 and 2, but in this paper, n will be large as 20 (maybe larger than 20) and high nonideality factor n shows that this model has no physical background, but only is a parametric model; V_T is thermal voltage, at room temperature (25 ℃), the thermal voltage is about 25.7 mV[10].

Before fitting measured OLED data, we choose the initial value of resistors R_1, R_2, R_s by rule of thumb, which is 1×10^{11}, 1×10^{7}, 1×10^{-4} respectively. According to Ref. [9], the capacitance is approximately 25 nF/cm^2, so the capacitor C for a 14.5 × 14.5 μm^2 pixel is 52.6 fF.

So to fit SPICE models to measured OLED data (Fig. 2),

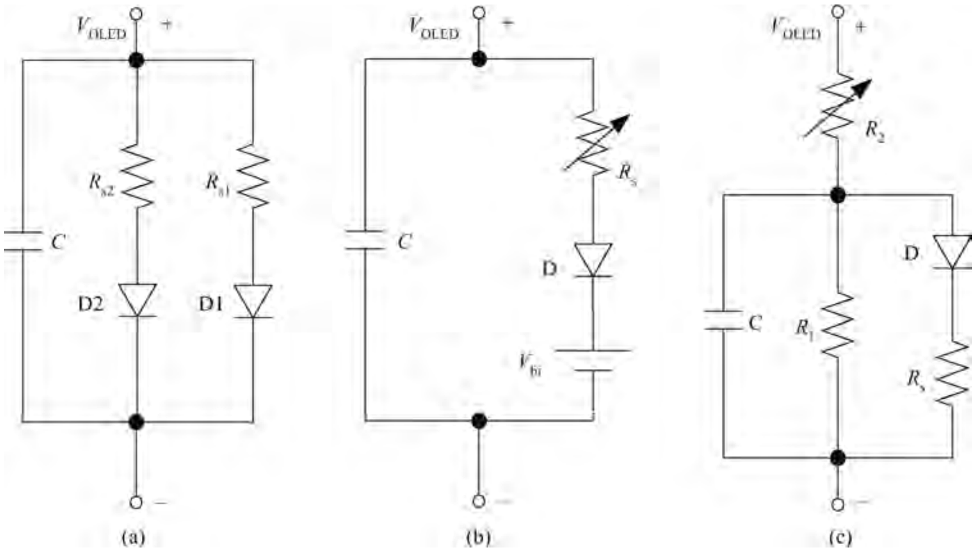


Fig. 4. Three kinds of OLED simplified model. (a) Double-diode paralleled model. (b) Physical-based model. (c) Single-diode OLED model.

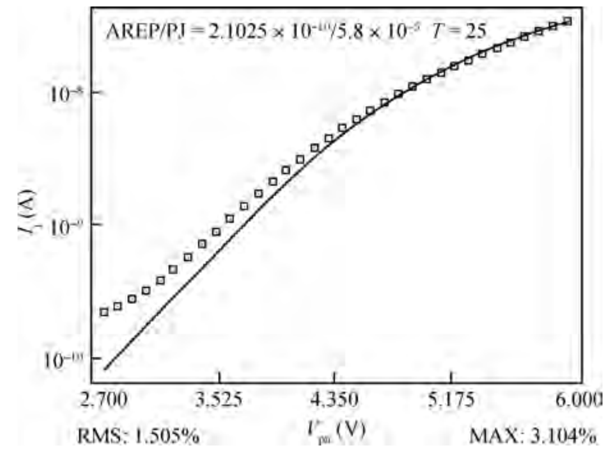


Fig. 5. Fitted SPICE models to measured OLED data results (log scale). The solid line is the simulation result, and square boxes indicate experimental data.

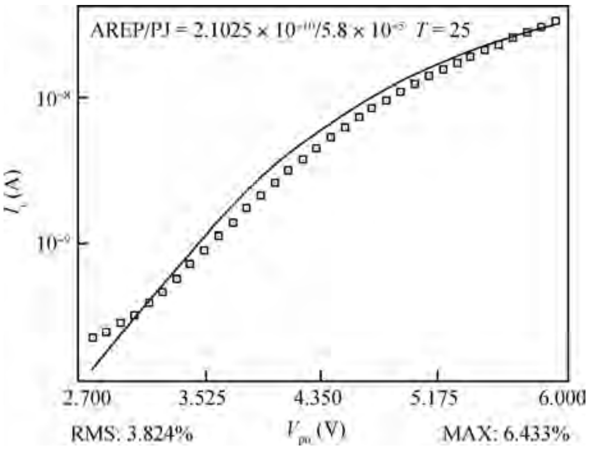


Fig. 6. Fitted SPICE models to measured OLED data with non-linear resistor R_2 (log scale).

the resistors (R_1, R_2, R_s) and diode D model parameters are determined through MBP optimization simulations. The fitting results are shown in Fig. 5, and we found that the simulation results did not fit very well to measured OLED data when the input voltage was in the vicinity of 3.5 V. Accordingly, to fix this problem we change the resistor R_2 from constant to variable resistance (it value is 'res/v(a)', v(a) means the voltage of the OLED's anode) and the fitting results are shown in Fig. 6. It shows that the fitting result has been improved when the input voltage is relatively low; however, the error is larger than before (in Fig. 5) when input voltage is larger than 4.5 V.

In order to get better agreement between experimental and simulated data, we need a resistor R_2 whose value decreases with input voltage increasing and can rapidly decrease when input voltage increases linearly. In that way, we choose the value of resistor R_2 to satisfy the following equation:

$$R_2 = \text{res2} \times \mathrm{e}^{\text{num} \times v(\text{a})(\text{volt} - v(\text{a}))} + \text{res3}, \tag{3}$$

where res2, res3, num, volt are coefficients and their initial value is 10^8, 10^7, 1, 3.5, respectively; v(a) is the voltage of the OLED's anode.

We add the modified OLED SPICE model to MBP and all parameters are determined through optimization simulations. As shown in Fig. 7, the experimental data fitted very well to the simulated data and it can easily satisfy the need for simulation accuracy. In addition, we fitted the measured OLED data with a double-diode paralleled model (Fig. 8(a)) and a physical-based model (Fig. 8(b)) through MBP optimization simulations. From the modeling results shown in the Fig. 8(a), the double-diode paralleled model has a deviation between the simulated current and the measured current when the operating voltage was about from 5 to 6 V; and in Fig. 8(b), it encountered a large error if we used a physical-based model to predict the current of the OLED at a low operating voltage. Meanwhile, comparing the result in Fig. 7 with Fig. 8, the RMS error and MAX error of the modified single-diode OLED model is less than that of the double-diode paralleled model and the physical-based model. That is to say, the new OLED model, which is modified based on the single-diode OLED model, has

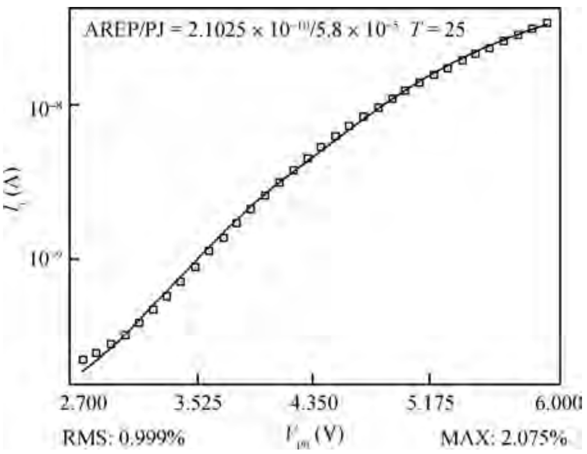


Fig. 7. Fitted SPICE models to the measured OLED data with exponential resistor R_2 (log scale).

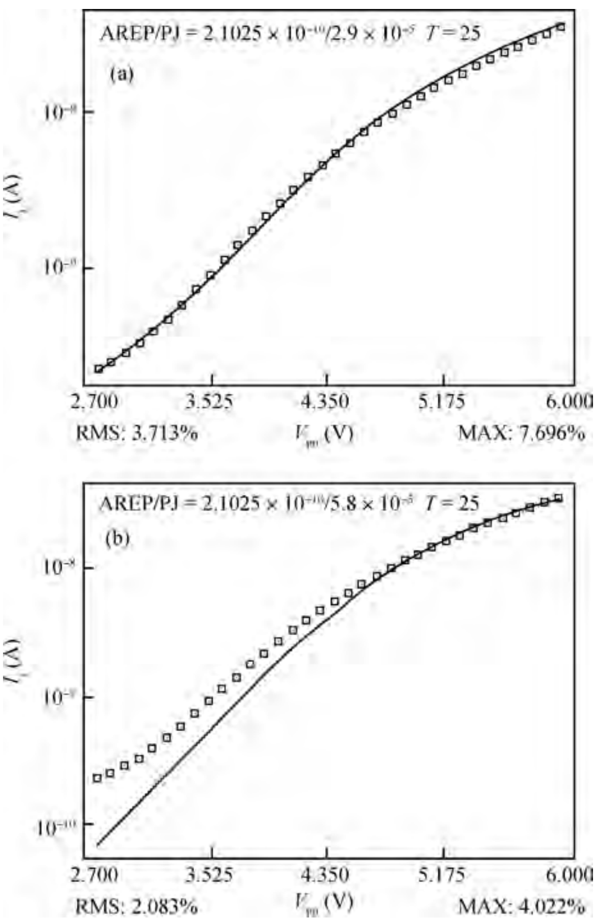


Fig. 8. Fitted measured OLED data with (a) the double-diode paralleled model and (b) the physical-based model (log scale).

good agreement between the measurement and simulation over the whole operating voltage range.

Furthermore, considering the cathode of OLED applied to –3 V, we modified Eq. (3) to:

$$R_2 = \text{res2} \times e^{\text{num} \times [v(\text{a}) + 3] \times [\text{volt} - v(\text{a}) - 3]} + \text{res3}. \quad (4)$$

Finally, we employ the following OLED SPICE model for

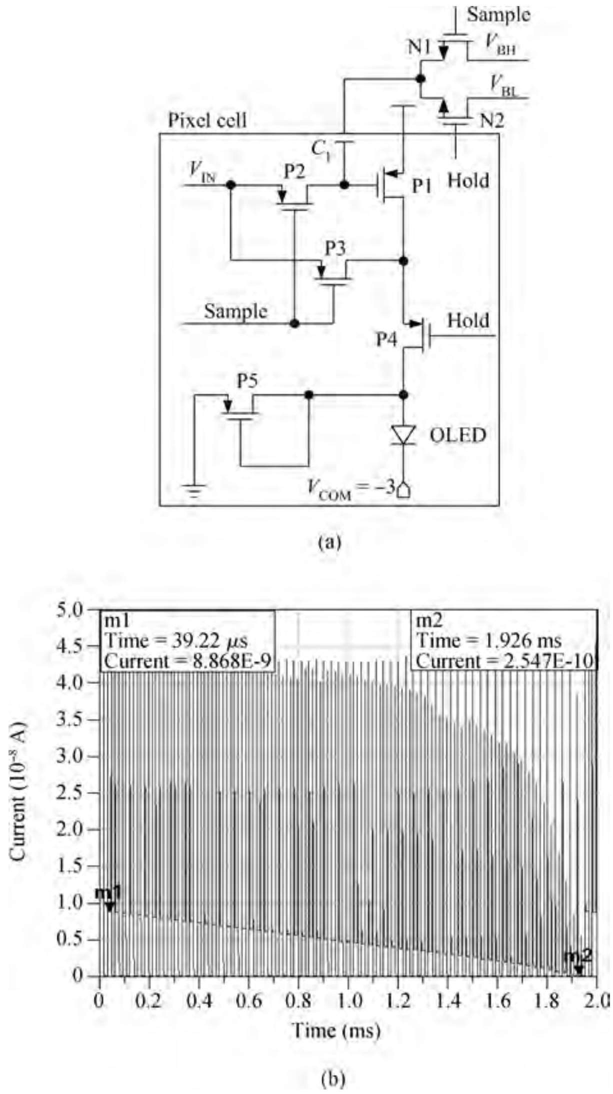


Fig. 9. (a) Subthreshold-voltage-scaling pixel circuit structure. (b) OLED working current simulation result with new model.

simulation:

.param

+ res = 9.6E8 res2 = 2.80135E8 volt = 4.13772 res3 = 1.23E7 num = 0.98

.subckt diodenew a b

C a b 52.6E-15

D1 c b diode AREA = 210.25E-12 PJ = 58E-6

R1 c b res

R2 a c 'res2 × exp((num × ($v(a)$ + 3)) × (volt − ($v(a)$ + 3))) + res3'

.model diode d

***** Flag Parameter ***

+ level = 1

***** DC Model Parameter ***

+ ibv = 1E-3 ik = 0 ikr = 0

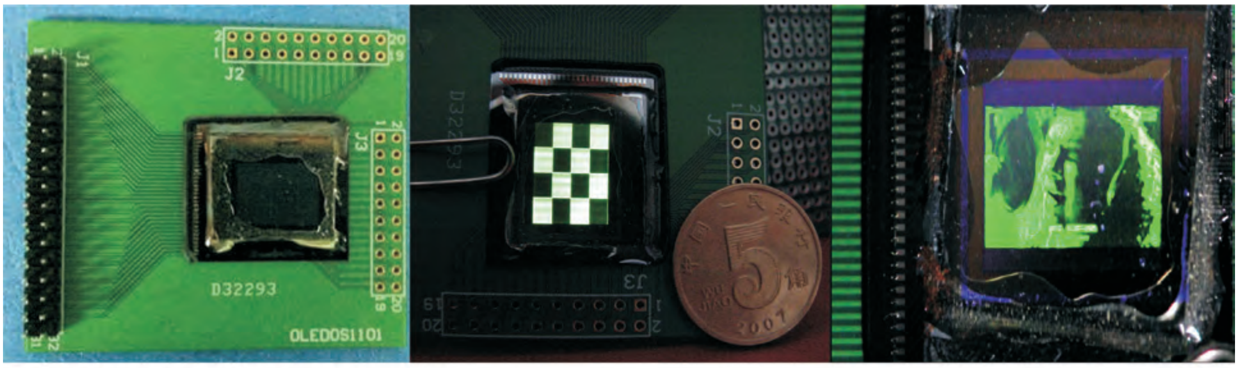
+ is = 2.353527E-4 jsw = 7.02E-10 n = 16

+ rs = 2.74E-3 bv = 0 nbv = 1

……

.ends diodenew

In Section 2, we have learned that the pixel operating current is as low as 324 pA, so the pixel circuit should modulate



(a) (b) (c)

Fig. 10. (a) OLEDoS chip with PCB package. (b) Black and white square pattern. (c) Playing a video.

Table 1. Measured current versus simulated current of one pixel cell with three OLED models.

6-bit DAC input	Luminance (cd/m^2)	Meas. (nA)	Sim. A (nA)	Sim.B (nA)	Sim.C (nA)
000000	17.9	0.31	0.24	0.16	0.06
000100	155.7	1.11	0.92	0.93	0.84
001000	297.7	1.91	1.66	1.61	1.48
001100	412	2.49	2.26	2.2	2.02
010000	495.7	2.93	2.83	2.76	2.57
010100	585.4	3.46	3.33	3.29	3.07
011000	668	3.89	3.84	3.86	3.62
011100	755.3	4.35	4.36	4.42	4.15
100000	825.3	4.75	4.83	4.96	4.67
100100	907	5.18	5.36	5.47	5.2
101000	983	5.61	5.86	6.05	5.73
101100	1063.3	6.03	6.37	6.58	6.25
110000	1128	6.39	6.89	7.14	6.77
110100	1206	6.84	7.41	7.67	7.31
111000	1274.3	7.19	7.94	8.21	7.85
111100	1356	7.65	8.47	8.76	8.38

pixel current at hundreds of picoamperes. So as to modulate the pixel current at such a level, three popular pixel circuit structures have been reported in Refs. [4, 11, 12]. Because the structure in Ref. [4], as shown in Fig. 9(a), has relatively low power consumption and can also work at a high sampling signal rate. We have applied it into OLEDoS microdisplay driving circuit design. We take the new OLED SPICE model which had been developed as pixel circuit simulation model. In addition, the aspect ratio of P1 is 6 μm/0.35 μm; P2, P3, P4, P5 are minimum-sized; in order to keep switch transistors N1, N2 having a fast response, the aspect ratio of N1, N2 are 10 μm/0.35 μm and V_{BH}, V_{BL} are low (such as 1.7 V, 1.4 V) relative to supply voltage (3.3 V). The working current simulation result of a single pixel cell is shown in Fig. 9(b) and it is modulated from 254.7 pA to 8.87 nA. According to the relationship between luminance and current density in Fig. 2, the brightness of an OLED will be approximate from 7 to 1500 cd/m^2 which can meet the requirements of contrast. Figure 9(b) also shows that the gradient difference between two adjacent output currents is uniform, that is to say, an OLED display can realize 64 gray scales.

4. Experiment results

A SVGA OLEDoS microdisplay driving circuit design, which has been taped out, adopted subthreshold-voltage-scaling pixel circuit. As shown in Fig. 10(a), the final chip with a PCB package and an OLEDoS device have been grown on the chip (the thickness of OLEDoS device is about 100 nm); a black and white square test pattern is displayed in Fig. 10(b); Figure 10(c) shows the OLED playing a video.

To estimate the OLED device's working current range, we measured the brightness of the OLED by using a Photo Research device (Spectra Scan 650) (it is difficult to acquire the working current of an OLED directly). So we got the results when V_{BH} is 1.7 V, V_{BL} is 1.4 V and input of DAC is from 000000 to 111100 (spacing is 4). We converted the brightness to current according to the relation between luminance and current density. Table 1 shows the experimental results and the three kinds of OLED model simulation results with Sim.A, Sim.B and Sim.C representing simulated current with our new model, double-diode paralleled model, and physical-based model, respectively. As described in Section 3, the double-diode paralleled model has a larger error at a high operating voltage than the new model, and the same situation appears in the physical-based model with a low operating voltage. Considering the accuracy of the Photo Research device and some other measurement random errors, the new SPICE model can more precisely simulate the actual working current of an OLED and it is very useful when we design OLEDoS microdisplay driving circuits.

5. Conclusion

In this paper, we have presented a new OLED SPICE model, which replaces the constant resistor with an exponential resistor based on a single-diode model. This model approximates the OLED behavior better than the other two OLED models that were proposed in Refs. [6, 7] and can be incorporated into circuit simulation without numerical difficulties. Experimental results show that the new OLED SPICE model can more precisely figure out the actual working current of an OLED as compared to the other two existing OLED models.

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