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A High Voltage NMOSFET Fabricated by using a Standard CMOS Logic Process as a Pixel-driving Transistor for the OLED on the Silicon Substrate

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Abstract

A high voltage NMOSFET is proposed to drive top emission organic light emitting device (OLED) used in the organic electroluminescent (EL) display on the single crystal silicon substrate. The high voltage NMOSFET can be fabricated by utilizing a simple layout technique with a standard CMOS logic process. It is clearly shown that the maximum supply voltage (V_{DD}) required for the pixel-driving transistor could reach 45 V through analytic and experimental methods. The high voltage NMOSFET was fabricated by using a standard 1.5 ㎛, 5 V CMOS logic process. From the measurements, we confirmed that the high voltage NMOSFET could sustain the excellent saturation characteristic up to 50 V without breakdown phenomena.

Keywords : High voltage MOSFET, standard CMOS logic process, pixel-driving transistor, top emission OLED, OLED on silicon substrate.

1. Introduction

Organic electroluminescent (EL) display in a single crystal silicon wafer is one of the emerging microdisplay technologies which can be applied to the head mount display for virtual images in military or medical equipment, wearable computer [1-3], and wrist-worn watch [4]. It consists of top emission organic light-emitting devices (OLEDs) on the CMOS integrated driving circuit, including peripheral row and column driving part as well as pixel array. Fig. 1 shows the cross sectional view of the OLED on a silicon substrate with a common anode structure.

OLEDs have many advantages such as simple device structure, high brightness, fast response time and low driving voltage. Also, silicon CMOS process is a very advanced technology that allows the integration of large-scale circuits. Further, the MOSFET device has superior electrical properties to the thin film transistor [5]. The OLED on the silicon substrate is the product of the combination of these two technologies.

Although the comparatively low operating voltage is one of the key advantages of organic EL devices, it is not easy to drive OLEDs directly with the conventional logic MOSFET because the driving voltage of OLEDs is usually higher than the MOSFET driving voltage. Therefore, a high voltage MOSFET is necessary to drive each OLEDs as a driving transistor of the pixel circuit [2], [6-7].

In this work, the high voltage MOSFET which was implemented using the conventional 1.5 μm, 5 V CMOS

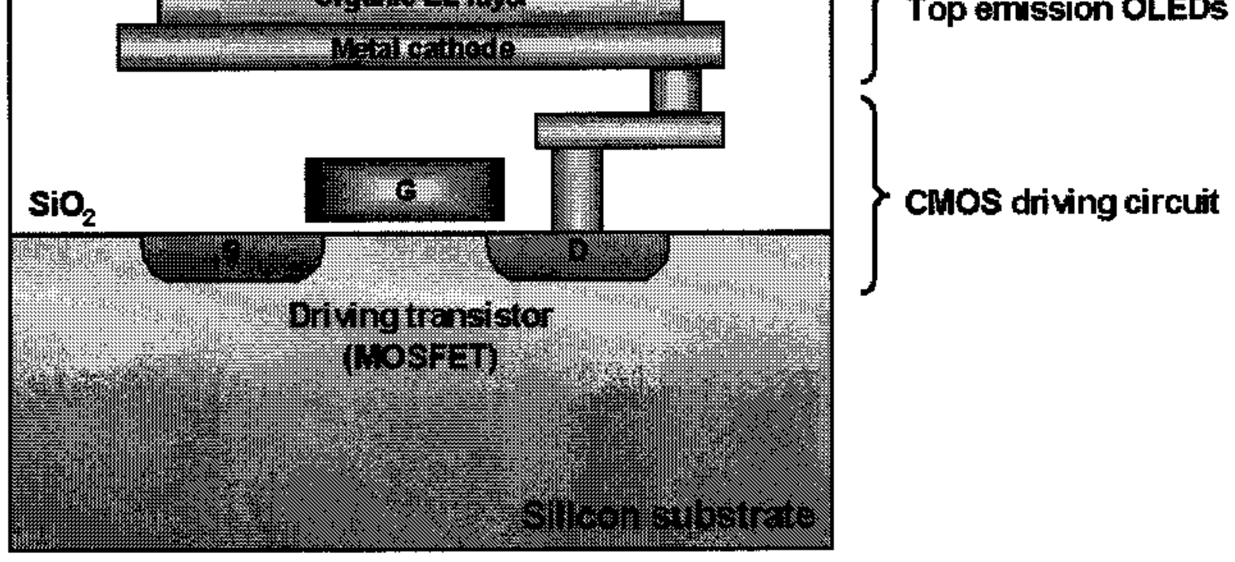

Fig. 1. Cross-sectional view of OELD on the silicon wafer. It is composed of top emission OLEDs on the CMOS driving circuit.

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logic process is proposed. And we confirmed that it can be used as a driving transistor of OLEDs on the silicon substrate.

2. Operating Voltage Requirement for the Pixel-driving Transistor

OLED is a current driving device whose brightness is proportional to the amount of current flowing through it, which means that it should be driven by a current source [7-10]. Therefore, the driving transistor in the pixel circuit shown in Fig. 2 must be operated in the saturation region because the MOSFET device can be approximated to an ideal current source in this region [11]. Therefore, it is necessary to clarify the general condition for driving MOSFET to be operated in the saturation region.

2.1 Analytical approach

Fig. 3 illustrates the load line of an OLED (I_{OLED}) and I_{DS}-V_{DS} characteristic of the driving MOSFET (I_{MOSFET}) in the pixel circuit as shown in Fig. 2. The intersections of two curves are quiescent points, and these points should exist in the saturation region. In addition, the maximum current, '$I_{EL,max}$', of the organic EL device can be chosen to obtain the peak brightness [7]. From Fig. 3, it is obvious that the maximum drain voltage V_{DD} of the driving MOSFET should satisfy the criteria (1) to guarantee the operation in the saturation region.

$$V_{DD} \geq V_{EL,max} + V_{dsat,max} \tag{1}$$

where $V_{EL,max}$ is the OLED voltage between anode and cathode when the current is equal to $I_{EL,max}$, and $V_{dsat,max}$ is the drain saturation voltage of the driving MOSFET at the same current value.

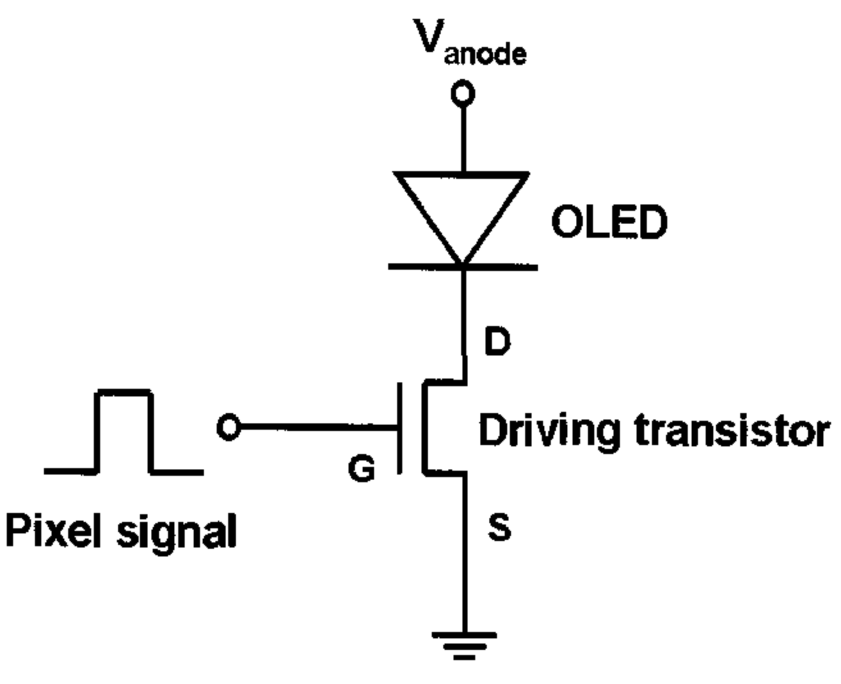


Fig. 2. Pixel driving circuit for the OELD on the silicon substrate with the common anode structure.

From the basic MOSFET equation at the saturation region [12], $V_{dsat,max}$ can be expressed as;

$$V_{dsat,max} = \sqrt{\frac{2I_{EL,max}}{\mu_{FET}C_{ox}\frac{W}{L}}} \tag{2}$$

where μ_{FET} is the mobility, C_{ox} is the gate oxide capacitance per unit area, and W and L are width and length of the driving MOSFET, respectively. Therefore, criterion (1) becomes

$$V_{DD} \geq V_{EL,max} + \sqrt{\frac{2I_{EL,max}}{\mu_{FET}C_{ox}\frac{W}{L}}} \tag{3}$$

The above condition (3) is the maximum voltage requirement for the driving MOSFET in the pixel circuit. In other words, the drain current should sustain a perfect saturation characteristic up to $V_{DS}=V_{DD}$.

For criterion (3), μ_{FET} and C_{ox} are the process-dependent parameters that are fixed by the semiconductor process. In addition, even though the ratio of W/L is an adjustable design parameter, its impact on V_{DD} is limited. The values of $V_{EL,max}$ and $I_{EL,max}$ are the characteristics of the OLED itself in the pixel, and it is these values that determine the minimum required V_{DD} value. Therefore, it is necessary to fully know the electrical properties of the top emission OLED.

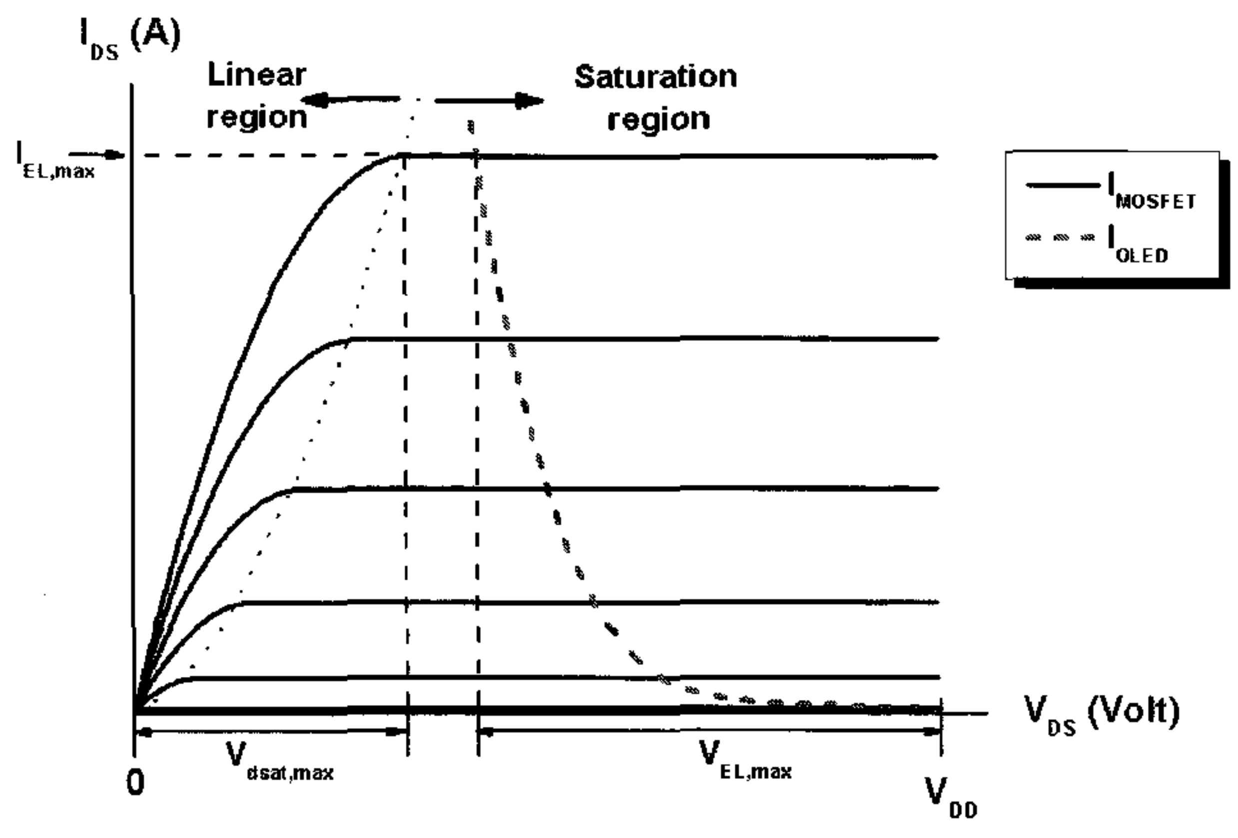


Fig. 3. Illustration of the load line of the OLED and I_{DS}-V_{DS} characteristic of the driving MOSFET in the pixel circuit. For the current driving, the quiescent points should be in the MOSFET saturation.

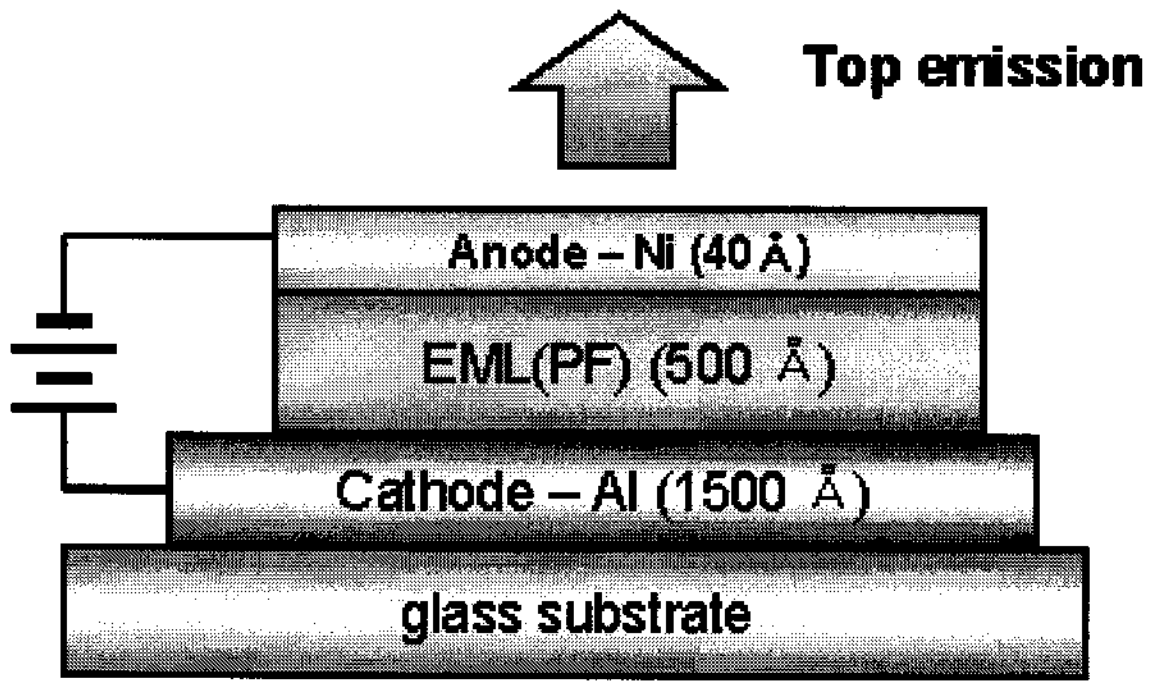
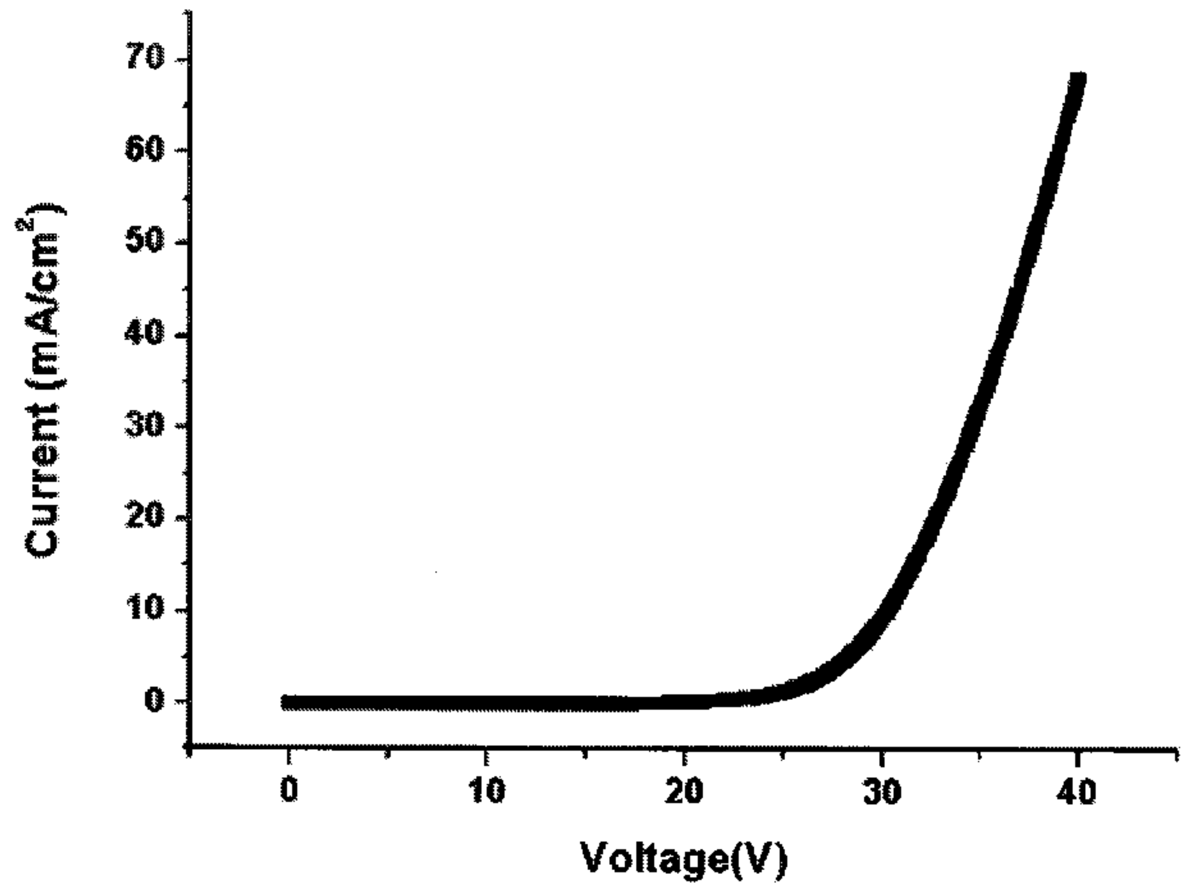
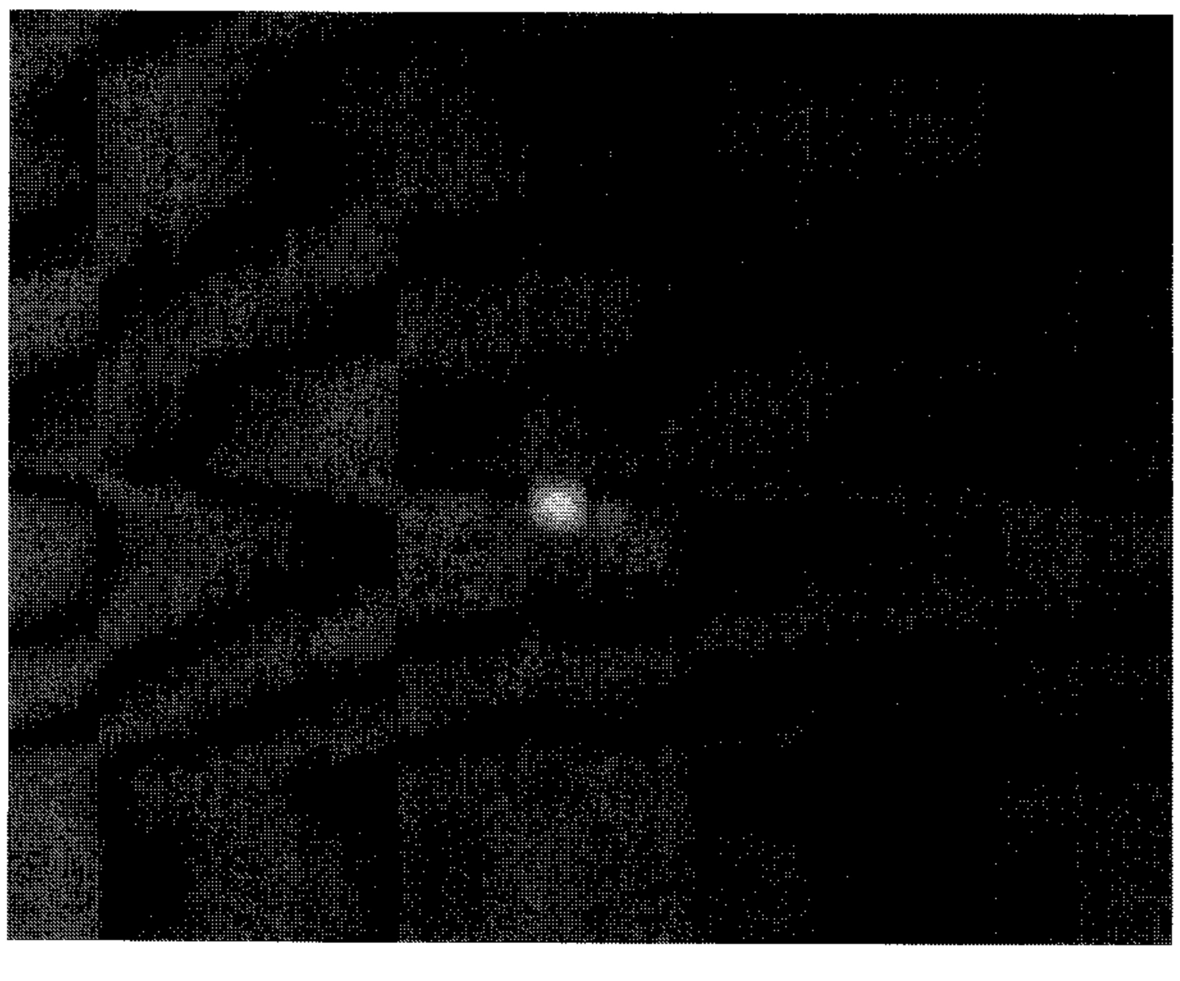


Fig. 4. Structure of the fabricated top emission polymer EL device.



(a)



(b)

Fig. 5. (a) I-V characteristic of the fabricated top emission polymer EL device. The turn-on voltage is 25 V, and the maximum operating voltage is 40 V. (b) Emission image at 40 V in the 10^{-4} Torr of vacuum chamber.

2.2 Experimental approach – fabrication of the top emission organic EL device

A simple top emission polymer EL device shown in Fig. 4 was fabricated to examine the electrical characteristics. At first, 1500 Å of the aluminum cathode was E-gun evaporated on the glass substrate through a shadow mask. Aluminum, whose work function is 4.28 eV [13], was selected because of its compatibility with the standard CMOS process when light-emitting layer is integrated on the driving circuit [5]. Then, 500 Å of the polyfluorene derivative green emitting polymer which is dissolved in chloroform was spin-coated. Finally, 40 Å of thin nickel, whose work function is 5.15 eV [13], was E-gun evaporated through a shadow mask to emit light upwards. All fabrication process was performed in atmospheric environment.

The electrical characteristic of the completed polymer LED was measured by using a HP 4155 A semiconductor parameter analyzer. The characterization was carried out in a vacuum chamber of 10^{-4} Torr. Fig. 5 (a) shows the measured I-V characteristic and Fig. 5 (b) shows an emission image at 40 V. The turn-on voltage is about 25 V and the maximum brightness is about 30 cd/m^2 at 40 V. These performances are relatively poor [14] perhaps due to single emitting layer, high work function cathode, thick anode, and fabrication environment. This performance can be improved by using transporting layers, inserting thin insulator (e.g. LiF) between Al and emitting layer [15], introducing low work function cathode and optimizing the thickness of thin anode.

Based on the calculation from equation (3), to drive the top emission OLED fabricated in this work, the minimum supply voltage of the driving transistor must be approximately 40.3 V, assuming μ_{FET} = 542 cm^2/V·sec, C_{ox} = 138 nF/cm^2 [16], W/L = 2 and 100 μm×100 μm pixel. In other studies conducted with a similar structure [14], [17-19], the minimum supply voltage of the driving transistor may be estimated to be about 45 V when the same calculation is carried out. These results imply that it is difficult to drive top emission OLEDs directly with the conventional logic MOSFET, and thus a high voltage MOSFET is necessary to drive OLEDs as a pixel-driving transistor.

3. High Voltage MOSFET Implemented with the Conventional Standard Process

From the above discussion, it can be concluded that a high voltage MOSFET is necessary to drive top emission OLEDs for the organic EL display on the silicon. This means that it is indispensable to use high voltage MOSFET process when fabricating the driving circuit. Fig. 6 shows the cross-section of a conventional high voltage MOSFET. There is a drift region (extended drain region) where the strong electric field can be dispersed around the drain area. Compared with the standard logic MOSFET process, the conventional high voltage process requires additional mask steps to form this drift region, which entails process complexity and high cost.

To overcome these drawbacks, we propose a high voltage NMOSFET that can be implemented by utilizing the standard CMOS logic process [20,21], as a driving transistor for OLEDs on silicon substrate. The HV NMOS can be easily implemented by the simple layout technique. The key idea is here that the drift region of the conventional high voltage process is replaced by n-well of the standard logic process instead of the drift region of the

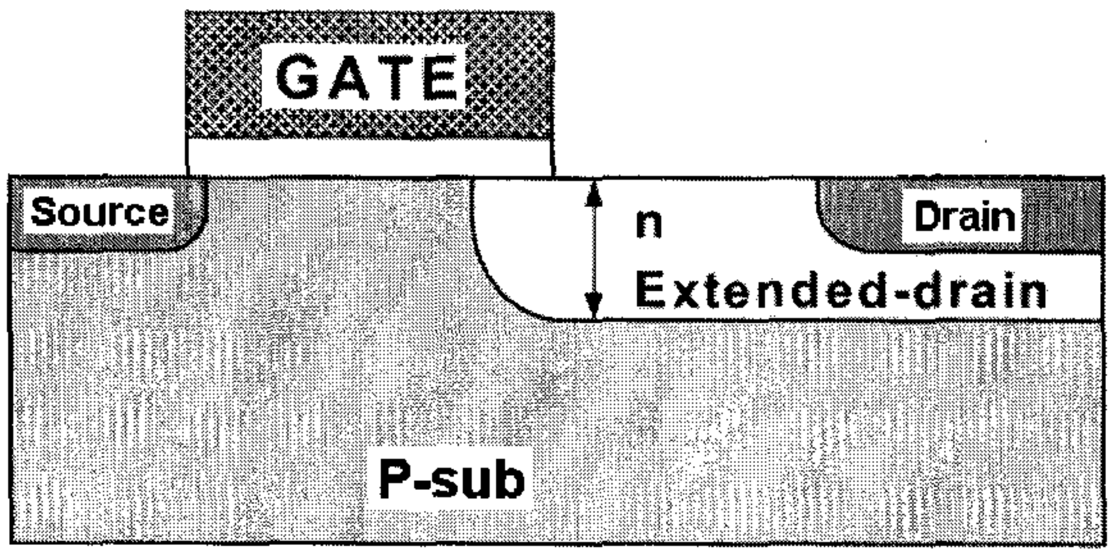


Fig. 6. Cross section of a conventional high voltage MOSFET. It has the drift region (extended drain region) to disperse the strong electric field around the drain region.

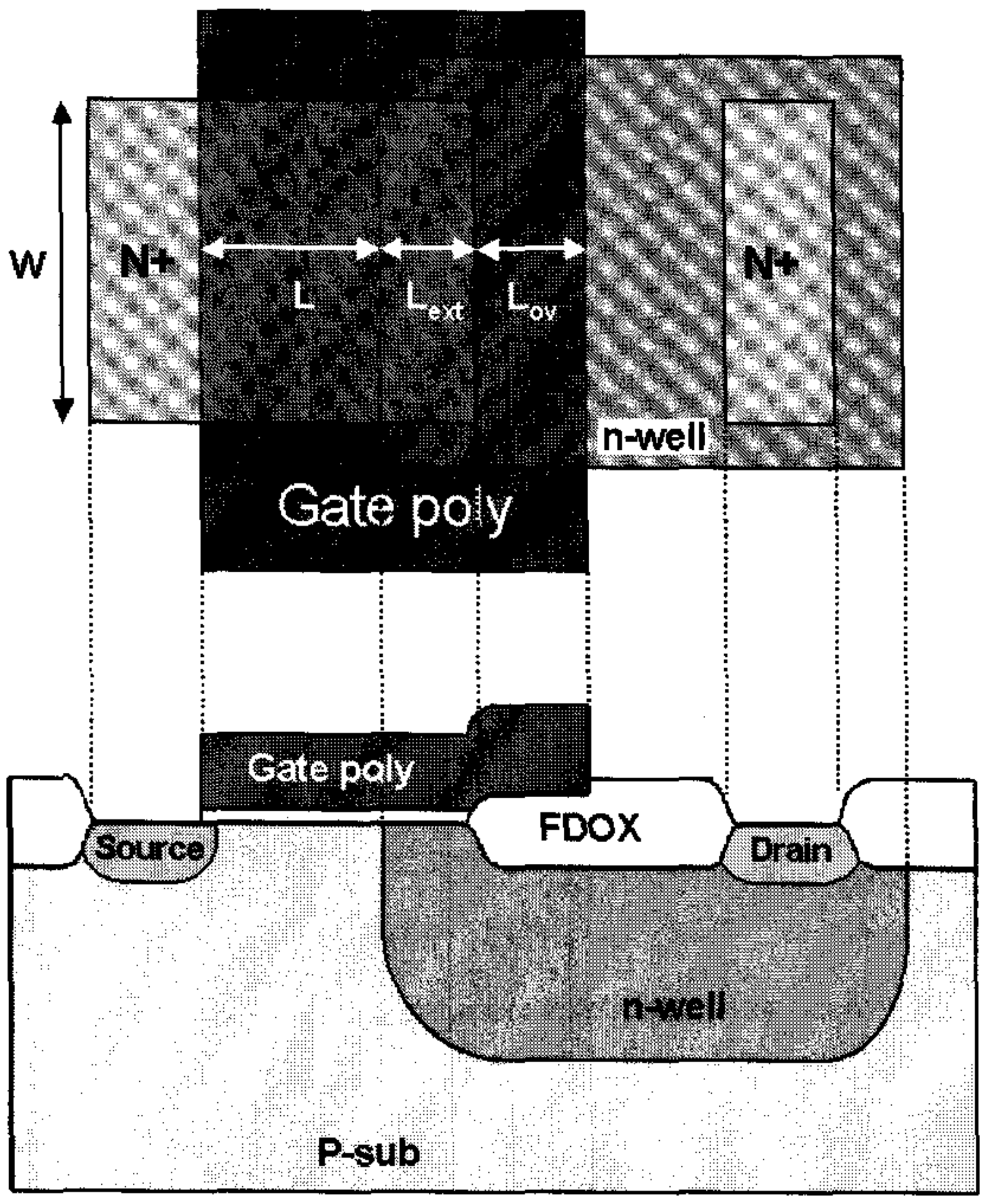
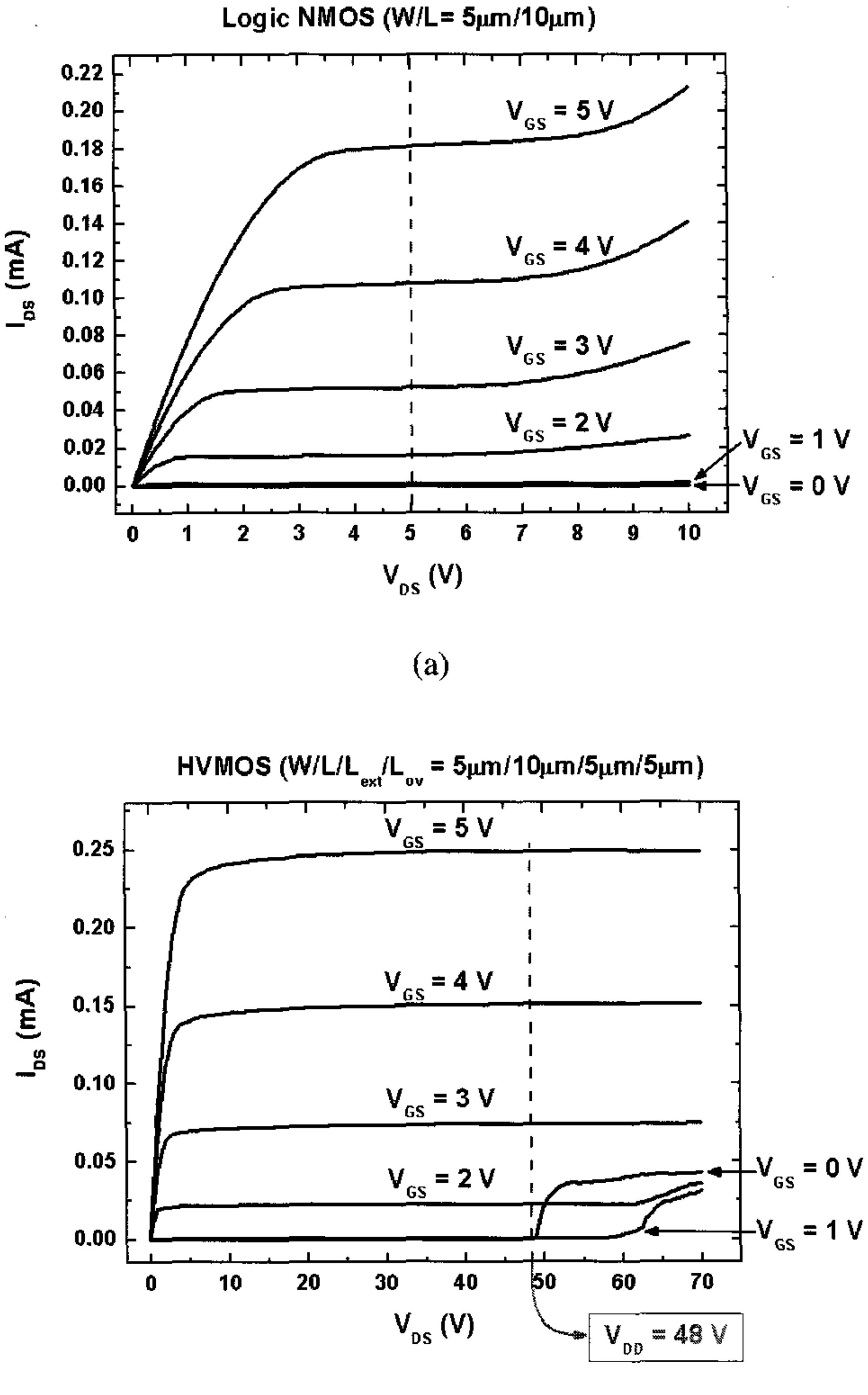


Fig. 7. Layout and cross section of the proposed high voltage MOSFET according to the standard 1.5 μm, 5 V CMOS logic process design rule. The low-doped n-well layer replaces the extended drain layer of the conventional high voltage MOSFET.



(a)

(b)

Fig. 8. Measured output characteristics of (a) the logic NMOS and (b) the high voltage MOSFET implemented by a standard 1.5 μm, 5 V CMOS logic process. In contrast with the logic NMOS, the high voltage MOSFET shows an excellent saturation characteristic up to 50V.

conventional high voltage process. Fig. 7 depicts the layout and cross-section of the proposed high voltage MOSFET according to the standard logic process design rule. The low-doped n-well region disperses the strong electric field of the drain. This technique has the advantage in that the high voltage MOSFET can be fabricated with the logic MOSFET on the same chip, without the need to modify any of process steps in the standard logic process.

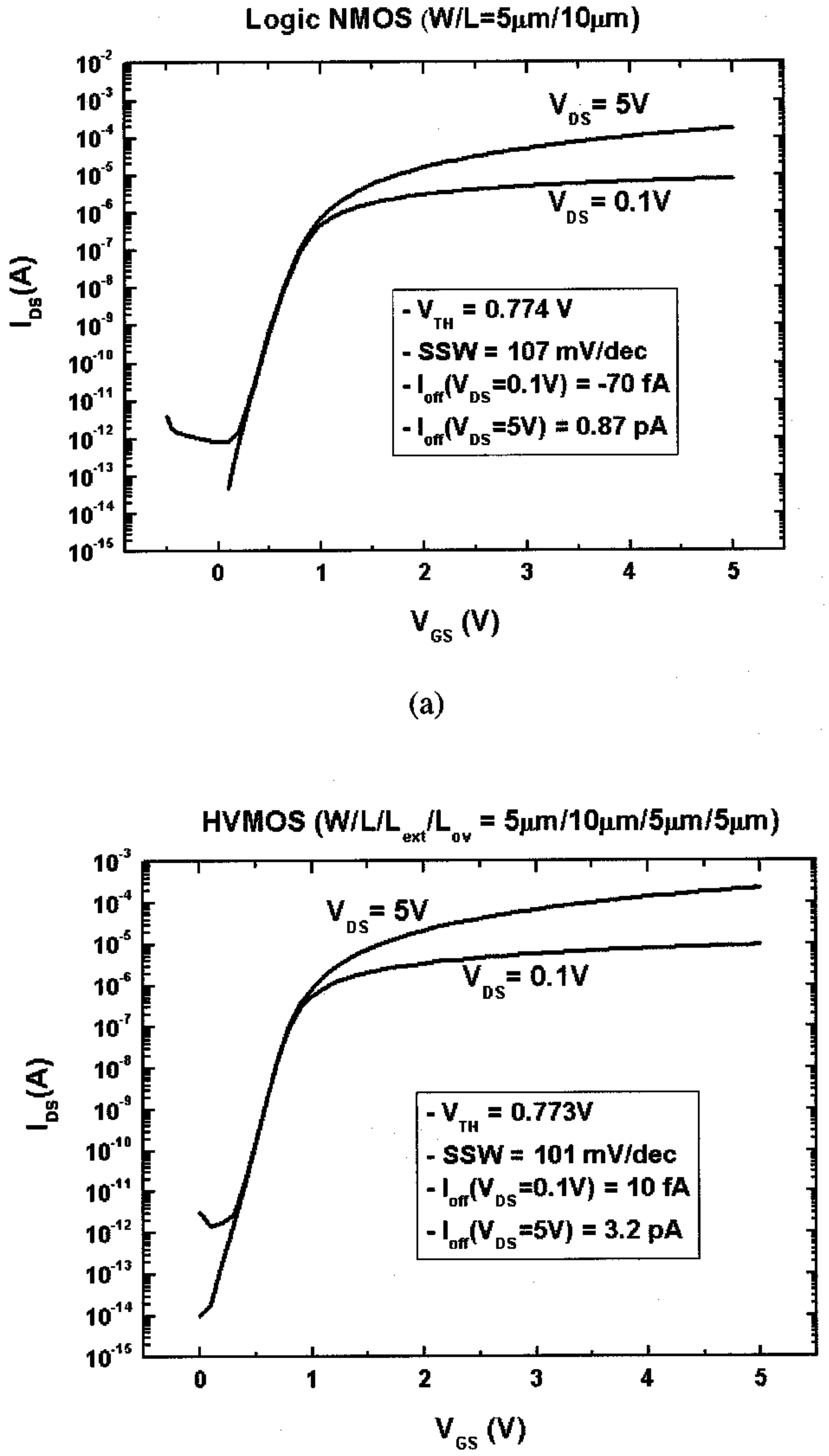
To confirm whether the high voltage MOSFET satisfies the supply voltage (V_{DD}) requirement of the pixel-driving transistor, the high voltage MOSFET was fabricated by using a standard 1.5 μm, 5V CMOS logic process [16]. The thickness of gate oxide was 250 Å, which is the same as the high voltage MOSFET. For comparison, the common logic NMOS was fabricated at the same time.

Fig. 8 shows the measured output characteristics of the fabricated logic NMOS and high voltage NMOS. The high voltage MOSFET sustains an excellent saturation characteristic up to 50 V, in contrast with the logic NMOS which reveals the breakdown phenomena when V_{DS} is below 5 V. This is a sufficient condition to drive top emission OLEDs directly, which means the high voltage MOSFET is able to satisfy the drain voltage requirement as a pixel-driving transistor. In addition, the excellent saturation characteristic supports the high image uniformity because it means that the operation of the driving transistor is close to that of the ideal current source.

Although the breakdown voltage of the proposed HV MOSFET is rather high, this is not a problem when driving the low-voltage operation OLEDs, for example, small molecular organic materials, because the anode voltage (V_{anode} of Fig. 2) may be lowered within the range such that all of operating points in the load line exist in the saturation region of the driving HV MOSFET. In addition, the maximum voltage drop between the anode and cathode of OLED is not ideally affected by the characteristic of the driving transistor with a constant $I_{EL,max}$, as is inferred from the load line in Fig. 3. Also, the relatively high saturation current of the proposed HV MOSFET can be reduced by adjusting the W/L ratio.

The measured transfer characteristics as shown in Fig. 9, is similar to that of the logic NMOS from the viewpoint of the threshold voltage and subthreshold swing (SS). Furthermore, the maximum gate voltage of the proposed high voltage is equal to that of the logic NMOS as the gate oxide thickness, 250 Å, of the former is the same as that of the latter. These factors imply that the gate of the high voltage MOSFET could be driven by the conventional CMOS logic driving circuit without any voltage level shifting circuit.

The saturation current variation of the proposed HV MOSFET, which includes the variation of the threshold voltage and mobility, is less than 1 % in a same die because the substrate is a single crystal silicon. This demonstrates one of the advantages of the organic EL display implemented on the silicon substrate. The drain leakage



(a)

(b)

Fig. 9. Transfer characteristics of (a) the logic NMOS and (b) the high voltage MOSFET. Two graphs shows the similar characteristic in threshold voltage and sub-threshold swing (SS).

current at $V_{GS}=0$ V, $V_{DS}=48$ V is about 68 pA, which is quite a small value. It affects to the contrast ratio though it depends on the design of the driving circuit. Therefore, it can be inferred that the high contrast ratio will be possible. In fact, we confirmed that the maximum contrast ratio could reach more than 500:1 from the electrical measurement of the conventional pixel circuit that is composed of 2 transistors and 1 capacitor.

The total layout area of the proposed HV MOSFET is somewhat large due to the drain extension region and relatively large gate length. However, the occupied area by the high voltage MOSFET did not exceed about 25 μm × 20 μm. The actual pixel layout showed that the resolution exceed at least 300 ppi when we used the proposed HV MOSFET as a pixel-driving transistor.

4. Conclusions

As the driving transistor for the OLED on the silicon substrate, high voltage MOSFET was fabricated and its electrical characteristics were examined. This experiments carried out by a simple layout technique, using the standard CMOS logic process without any additional mask steps for the high voltage MOSFET. The measured output characteristic showed that the fabricated high voltage MOSFET satisfied the maximum drain supply voltage (V_{DD}) specification sufficiently. Based on these experimental results, we concluded that the high voltage MOSFET, which was implemented by using a standard CMOS logic process, is a good candidate as the driving transistor for the OLED on the silicon.

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