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A metal-oxide field-effect transistor (MOSFET) based on an electroluminescent conjugated polymer is fabricated on a glass substrate. It is found that the mobility horizontal to the substrate is two to three orders of magnitude larger than the mobility vertical to the substrate. The high horizontal mobility is attributed to the in-plane chain alignment in amorphous spin-coated films. We demonstrate an active pixel in which the light-emitting diode and the driving MOSFET share the same active polymer. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1644322]

Light-emitting diodes (LED) and metal-oxide field-effect transistors (MOSFET) are the two building blocks of most semiconductor optoelectronic devices, in which the MOSFET performs signal processing while the LED converts the electric signal into optical output. So far, in almost all devices, LEDs and MOSFETs use different semiconductors as the active material, because in general, the semiconductors good for MOSFETs do not emit light, while the luminescent semiconductors do not exhibit good MOSFET characteristics. On the inorganic side, Si is ideal for MOSFET but is not luminescent, while III-V compounds are good for LEDs but are difficult to form into oxides. On the organic side, the carrier mobilities of the highly electroluminescent (EL) conjugated polymers poly(p-phenylene vinylene) (PPV) and polyfluorene (PF) appear too low for transistors. Pentacene and poly(3-hexylthiophene) (P3HT) have higher mobility, but their excitons decay nonradiatively due to symmetry in ordered structure.[1] The integrated optoelectronic devices would be highly simplified if LED and MOSFET share the same semiconductor. One of the most promising application of conjugated polymer semiconductor is active matrix flat-panel display,[2] in which each active pixel contains a LED driven by a MOSFET. PPV and PF are usually used for LEDs. Silicon,[3] pentacene,[4] and P3HT[5] have been used for MOSFETs. In addition to the higher vacuum cost for silicon and pentacene, the semiconductors for LEDs and MOSFETs need to be precisely deposited at their respective positions. It would be highly desirable if the LED and the MOSFET use the same EL polymer, which can then be spin-coated in large area without the necessity to be precisely patterned. Optical study has revealed that in spin-coated film the polymer

chains are mostly aligned along the substrate due to the centrifugal force during the spin.[6] The performance of the MOSFET therefore depends on whether the alignment raises the mobility horizontal to the substrate substantially above the low vertical mobility commonly observed in the sandwich LED structure. We fabricate MOSFETs based on highly luminescent poly [2-methoxy-5 (2′-ethyl-hexyloxy)-1,4-phenylene vinylene] (MEH-PPV) on glass, and show that the horizontal mobility can be more than 500 times larger than the vertical mobility. Such a MEH-PPV MOSFET on glass is ready to be integrated with a standard MEH-PPV LED. We demonstrate the first active pixel (Fig. 1) using only one kind of semiconductor. Independent mobility measurement is performed by fitting the space-charge-limited current (SCLC) in horizontal electrodes (no gate). The result is consistent with the field-effect mobility in the MOSFET.

The structure of the MOSFET is shown in Fig. 1. Indium tin oxide is used as the gate. SiO_2 gate insulator of 3000 Å is grown by atmospheric pressure chemical vapor deposition. Gold source and drain (2000 Å) are thermally evaporated then patterned by photolithography and lift-off. The channel length L is 2 μm and the width W is 200 μm. The leakage current through the gate insulator is below 1 nA when the source–gate bias is 40 V. MEH-PPV with molecular weight
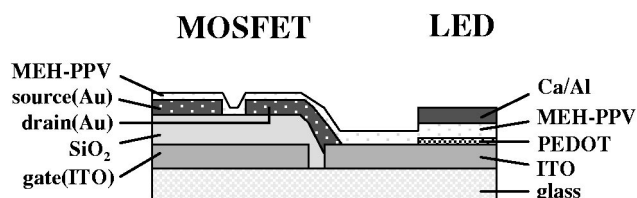

FIG. 1. The structure of the active pixel. MEH-PPV is the shared active semiconductor for the MOSFET and LED.

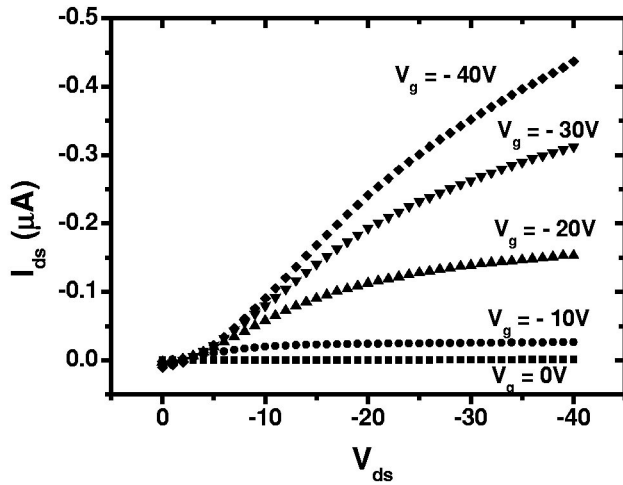[a] Electronic mail: meng@cc.nctu.edu.tw

FIG. 2. The source–drain I–V of the MOSFET is shown for various gate voltages.

FIG. 3. (a) The LED brightness and current is shown as functions of the applied voltage. The LED area is 100 μm$\times$200 μm. (b) The LED emission recorded by the photodetector is plotted as a function of the MOSFET gate voltage.

$M_w = 10^6$ is synthesized[7] and dissolved in chloroform with weight percentage 0.5 wt %. The 1000 Å polymer film is spin-coated at 4200 rpm and baked at 70 °C in vacuum (2 $\times 10^{-2}$ Torr) for 60 min. The device is packaged in a nitrogen glove box and measured in air. The LED is also shown in Fig. 1. Poly(3,4-ethylenedioxythiophene) (PEDOT) doped with polystyrene sulphonated acid is used as the hole transport layer.

The transistor characteristics measured by HP4156A semiconductor parameter analyzer is shown in Fig. 2. The source is the common ground whose voltage is taken as zero. Good transistor action is seen in the hole accumulation mode ($V_g < 0$). The largest drain current I_d reached at $V_d = V_g = -40$ V is 450 nA. The drain current on-off ratio between $V_g = 0$ and $V_g = -40$ V at $V_d = -40$ V is 390. After an initial linear rise with V_d, I_d starts to level off at $V_d = V_g$. The I_d–V_d curve, however, never saturates to a constant. This results from the competition between the pinch-off and SCLC. The horizontal field-effect mobility μ_h^f is obtained from the saturation current $I_{ds} = (W \mu_h^f C_{ox}/2L)(V_g - V_0)^2$ at the saturation voltage $V_d = V_g$. $C_{ox} = 11.5$ nF/cm^2 is the SiO$_2$ capacitance per unit area. The threshold voltage $V_0 = 2$ V is obtained by plotting $\sqrt{I_{ds}}$ against V_g to extrapolate the voltage with $I_{ds} = 0$. μ_h^f is 5.5×10^{-4} cm^2/V s at $V_g = -20$ V, and 4.3×10^{-4} cm^2/V s at $V_g = -40$ V. The mobility can also be obtained from the linear region drain current $I_d = (W \mu_h^f C_{ox}/L)(V_g - V_0) V_d$. For $V_d = -10$ V, we have $\mu_h^f = 3.3 \times 10^{-4}$ cm^2/V s. The mobility in the saturation region is higher than that in the linear region because the mobility is expected to increase exponentially with the square root of the horizontal field (Poole–Frenkel form), typical for disordered materials.[8] The horizontal mobility is 2–3 orders of magnitude larger than the vertical mobility μ_v ($\sim 10^{-6}$ cm^2/V s) in sandwich structure for MEH-PPV, as discussed later. μ_h^f has been measured on Si substrate with thermal oxide as the gate insulator.[9] Even though the fabrication on Si is more standard, the reported μ_h^f is smaller than the mobility in our device on glass. Apparently the material quality and device processing condition play major roles to determine the final MOSFET performance.

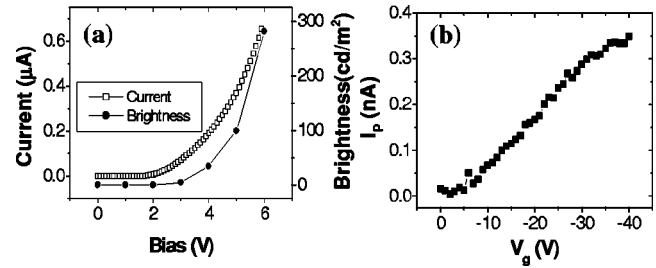The characteristics of a 100 μm$\times$200 μm MEH-PPV

LED (typical pixel size) is shown in Fig. 3(a). The brightness reaches 100 cd/m^2 for current of 400 nA. Comparing Fig. 2 and Fig. 3(a) it is clear that the MOSFET is good enough to drive a LED in the integrated active pixel structure shown in Fig. 1. We actually made such an integration, and the result is shown in Fig. 3(b). The light emission of the (100 μm $\times$200 μm) LED is detected by a photodetector in closed circuit. The photocurrent I_p is proportional to the LED brightness. For V_d fixed at 40 V, I_p is shown to increase with the gate voltage V_g. In other words, a MEH-PPV pixel is driven by a MEH-PPV MOSFET in an integrated structure. Positive V_d is used to enhanced the drain current.

In order to measure the hole mobility independently, horizontal gold electrodes are fabricated on glass (no gate and oxide). The height of the electrodes is 2000 Å, the channel length is 3 μm, and the width is 500 μm. The current density J_h is plotted in Fig. 4(a) as a function of the averaged electric field E. In SCLC, the current density is related to the field by $J = 9 \epsilon \mu E^2/8L$.[10] The mobility μ_h extracted from the J–E plot is shown in Fig. 4(b). For vertical mobility μ_v, we measure the J–E of the hole-dominated sandwich structure with the Ca/Al cathode replaced by Al cathode. $\epsilon = 3$ is used for the dielectric constants.[11] The results are also shown in Figs. 4(a) and 4(b) for comparison. The field dependence of the mobility follows the Poole–Frenkel form[8] $\mu = \mu_0 e^{\gamma \sqrt{E}}$. Considering a typical field $E = 2 \times 10^5$ V/cm (corresponds to $V_d = -40$ V over $L = 2$ μm in MOSFET), μ_v is 1.0×10^{-6} cm^2/V s. This value for μ_v is similar to what reported before for MEH-PPV.[8,12] μ_h is as high as 1.1 $\times 10^{-3}$ cm^2/V s, 1000 times larger than μ_v. μ_h is about twice as large than the field mobility of the MOSFET, perhaps due to the carrier traps in the oxide–polymer interface.

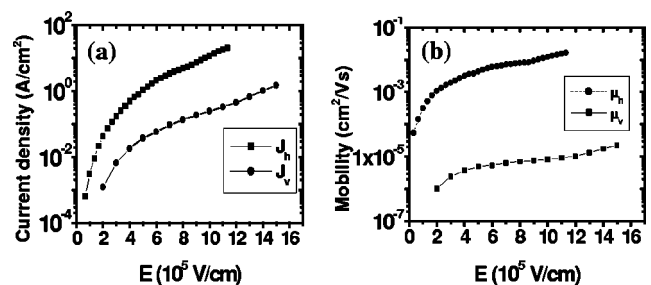The dramatic difference between the horizontal and ver-

FIG. 4. (a) J_h and J_v are the horizontal and vertical current densities in SCLC, respectively. (b) The horizontal mobility μ_h and vertical mobility μ_v of MEH-PPV extracted from SCLC are shown as functions of the electric field.

tical mobilities reflects the anisotropic morphology in which the polymer chains are mostly along the substrate.[6] Thus, in the sandwich LED, the carriers have to make an interchain hopping in order to move vertically. In the MOSFET, the carriers can move horizontally along a chain farther before making an interchain hopping. The horizontal hopping distance is related to the in-plane extension of the polymer chain. Because chloroform is a highly volatile solvent, the polymer film is solidified during the spin, and the extended chain morphology caused by the centrifugal force is likely to be frozen after the spin. Even though our mobility is still lower than ordered organic semiconductors like pentacene and P3HT, it should be noted that our film is amorphous, and the improved mobility is not due to the coherent band transport, but due to the anisotropic chain alignment. Considering the vast variety of amorphous EL polymers, it is expected that better active pixels can be made with further research on materials and morphology control. The polymer purity and handling after synthesis turn out to be critical to the device performance. The mobility deteriorates rapidly upon oxidation. The MOSFET used in Fig. 3(b) is actually not as good as the one in Fig. 2. More stable conjugated polymers are needed in order to make this idea practical. One great advantage of the one-polymer pixel is that MEH-PPV does not need to be patterned. The PEDOT over the MOSFET is removed by dissolving in water in our device. Considering the small MOSFET channel, the removal of PEDOT tolerates tens of microns of inaccuracy. In practice, PEDOT can be patterned by screen printing[13] or lithography.[14]

In conclusion, using MEH-PPV as a model, we demonstrate that a LED and a MOSFET in an active pixel can share the same semiconductor. The key to achieve this is that the horizontal mobility for the MOSFET in the spin-coated film can be three orders of magnitude larger than the vertical mobility for the LED.

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