Ambipolar organic light emitting field effect transistors with modified asymmetric electrodes

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The authors report on gate-controlled light emission from an organic field effect transistor composed of a vapor-deposited thin film of α,ω-bis(biphenyl-4-yl)-terthiophene (BP3T) with an electron injection layer of pentacene for the drain electrode. A n-triacontane thin film vapor deposited on a Si/SiO_2 wafer was used as a buffer layer for the gate dielectric. The location of emission zones within the channel where both injected carriers recombine was controlled by the gate voltage. The insertion of the pentacene and n-triacontane layers improved the threshold voltage and mobility for electrons, resulting in balanced ambipolar carrier injection and transport. *© 2007 American Institute of Physics*. [DOI: 10.1063/1.2719680]

Recently organic light-emitting field effect transistors (OLEFETs) have attracted much attention due to their potential applications for near-future organic optoelectronic devices. In the field of OLEFETs, the device performance has been rapidly improved in the past few years. There have been a lot of studies on OLEFETs fabricated with solution-processed polymer thin films and vacuum-deposited thin films of small molecules. Most of the reported devices until now have shown p-type unipolar behaviors and their light emissions are observed in the vicinity of the drain electrode.[1–3] More recently, some groups have demonstrated ambipolar OLEFETs using conductive polymers as the active channel and pure nonpolar polymer dielectrics as the buffer layer which prevent electron trapping at the dielectric-semiconductor interface.[4,5] In ambipolar OLEFETs the location of carrier recombination can be controlled within the channel region by the gate voltages (V_G), so that the emission quenching by the metal electrode can be suppressed. It is also known that efficient ambipolar charge injection in OLEFETs is achieved by using two different metals for the source and drain electrodes. Sakanoue *et al.*[6] demonstrated that the polymer OLEFET with asymmetric source/drain electrodes of Au/Al enhanced luminescence intensity.

However, there has been a problem of contact properties between the organic and metal interface which limits the carrier injection performance of OLEFETs. In particular, an ambipolar OLEFET requires the injection of both types of carriers into a single organic semiconductor. Most of organic materials for OLEFETs reported so far have a wide energy gaps between the highest occupied and lowest unoccupied molecular orbital (HOMO and LUMO) levels, and therefore there has been difficulty in achieving the ambipolar carrier injection.[7] In particular, a typical p-channel OLEFET has a high electron injection barrier between the organic layer and drain electrode. In order to decrease this injection barrier, in this work, we first used a low work-function Al:Li electrode, and secondary an electron injection layer of pentacene was inserted underneath the drain electrode. Furthermore, by coating the gate dielectric surface with a buffer layer of nonpolar alkane layer, highly balanced ambipolar carrier injection and transport were obtained. Finally, we achieved an emission-zone-controlled OLEFET fabricated with all vapor-deposited thin films of small molecules.

Figure 1 shows a schematic diagram of the fabricated device and chemical structures of α,ω-bis(biphenyl-4-yl)-terthiophene (BP3T).[8] We used BP3T as an organic semiconductor since this thiophene/phenylene co-oligomer has high carrier mobilities and proper HOMO/LUMO configuration for ambipolar carrier injection.[9] A p-doped Si wafer with a 400-nm-thick SiO_2 was used as the gate electrode. The SiO_2 layer was passivated with a vapor-deposited 35-nm-thick n-triacontane film. Then a 65-nm-thick BP3T was vapor deposited onto it. An electron injection layer of 15-nm-thick pentacene thin film with an area of 100 μm $\times$2 mm was partially deposited onto the BP3T layer through a shadow mask having a stripe hole (100 μm$\times$2 mm) aligning parallel with an interval of 200 μm. All of these organic

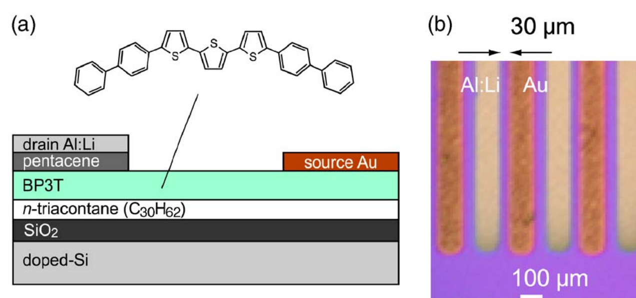

FIG. 1. (Color online) Schematic diagram (a) and top-view photograph (b) of BP3T-based OLEFET.

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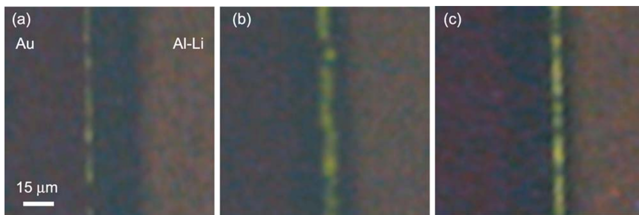

FIG. 2. (Color online) Optical micrographs of light emission from the channel region of BP3T-based OLEFET operated at constant $V_{\mathrm{DS}}=-200$ V and varied V_G of −80 V (a), −90 V (b), and −100 V (c).

layers were deposited using a conventional vacuum evaporator at room temperature under a pressure of 1×10^{-4} Pa. The deposition rates of *n*-triacontane, BP3T, and pentacene were 20, 6.5, and 6.5 nm/min, respectively. The Au source and Al:Li (99:1) alloy drain electrodes were patterned onto a desired position by manipulating the same shadow mask under microscopic observation to form a channel length (L) of 30 μm and width (W) of 2 mm, as shown in a micrograph in Fig. 1. For comparison, a reference device without pentacene layer was fabricated by the same procedures. Electrical measurements were performed with a Keithley model 4200 semiconductor characterization system at room temperature under a vacuum of less than 5×10^{-4} Pa. The above procedures from the electrode depositions to the electrical measurements were carried out without breaking the vacuum. The HOMO and LUMO levels of BP3T and pentacene were calculated by the density functional theory using an Accelrys MATERIAL STUDIO/DMOL^3 program.

Prior to fabrication of the device as shown in Fig. 1, we examined the property of OLEFET without the *n*-triacontane and pentacene layers. This device exhibited typical *p*-type unipolar characteristics with good saturation behavior at negative V_G while no electron current was observed at positive V_G. Light emission was observed only at the edge of the drain electrode where the electrons were thought to tunnel from the drain electrode into the organic semiconductor. On the other hand, Fig. 2 shows optical microscope images of light emission obtained from the device as shown in Fig. 1 at constant source-drain voltage (V_{DS}) of −200 V. At this V_{DS} and negative high V_G, the holes are injected from the Au source electrode while the electrons are injected from the Al:Li drain electrode, thus both carriers are recombined in the organic semiconductor layer. The line-shaped emission was observed within the channel, the position of which was varied depending on V_G. When $V_G > -80$ V, the emission zone was in the vicinity of the source electrode while it was close to the drain electrode at $V_G < -100$ V. At a small V_G range between −80 V and −100 V the emission line was transferred from the source Au electrode to the drain Al:Li electrode. These images suggest the coexistence of hole and electron accumulation in the BP3T layer. The width of the emission zone (7 μm at $V_G=-90$ V) seemed to be varied depending on V_G. Such V_G dependence of the emission zone and luminance is now under investigation. The gate-controlled light emission was also observed at the electron saturation regime at positive V_{DS} and V_G when the source electrode was connected to Al:Li and the drain to Au. The electron and hole mobilities were $\mu_e=2.94\times10^{-2}$ cm^2 V^{-1} s^{-1} and $\mu_h=9.13\times10^{-3}$ cm^2 V^{-1} s^{-1}, respectively, both calculated from the equation for the drain current at the saturation regime, $I_{\mathrm{D}}=(2W/L)\mu C_i(V_G-V_{\mathrm{TH}})^2$, where

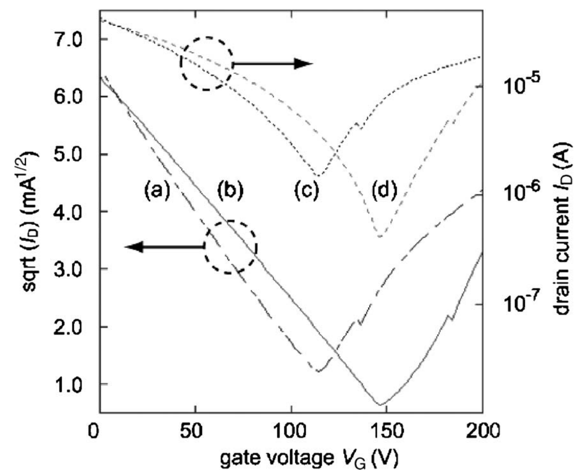

FIG. 3. $I_{\mathrm{D}}^{1/2}$-V_G and I_{D}-V_G characteristics for the BP3T-based OLEFET with [(a) and (c)] and without [(b) and (d)] injection layer of pentacene taken at constant $V_{\mathrm{DS}}=200$ V.

C_i is the capacitance per unit area of the insulating layer, and V_{TH} is the threshold voltage. These ambipolar mobilities are relatively higher than those reported for polymer-based OLEFETs.[4,5]

The contact property between the organic and metal interface strongly affects the performance of ambipolar OLEFETs. In the case of the BP3T-based device the gate threshold voltage for electron injection (V_{TH}^e) is usually high due to the existence of high potential barrier between the LUMO level and the Fermi level of metals. The effect of the pentacene layer inserted between the BP3T and the electrode is discussed by comparing the transfer characteristics in the *n*-channel accumulation region at constant V_{DS} (200 V). Figure 3 shows $I_{\mathrm{D}}^{1/2}$-V_G and I_{D}-V_G plots for the devices with the pentacene layer [(a) and (c)] and without it [(b) and (d)]. As clearly seen from the $I_{\mathrm{D}}^{1/2}$-V_G characteristics the threshold voltage shift for electron injection is about −40 V. This negative shift arises from the lowering of the electron injection barrier between the BP3T layer and Al:Li interface. The

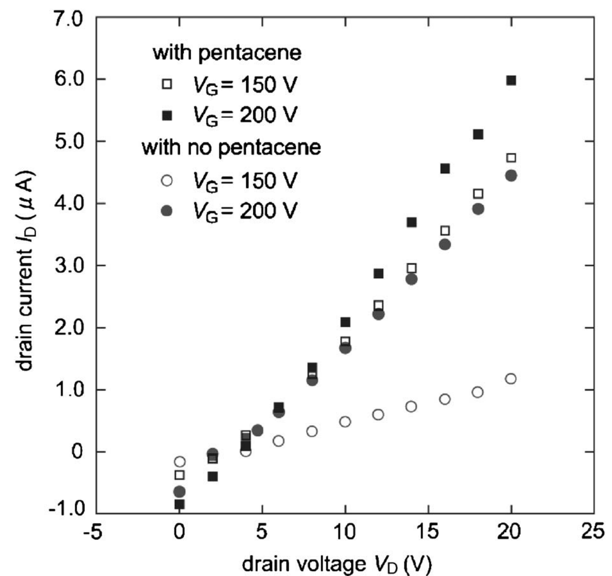

FIG. 4. I_{D}-V_G plots for the BP3T-based OLEFET with (square) and without (circle) injection layer of pentacene taken in the linear region at V_G =150 V (open) and 200 V (closed).

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LUMO level of pentacene calculated lies in −3.4 eV that is lower than that, −2.8 eV, of BP3T. Since the work function of Al:Li is close to 4 eV, the LUMO of pentacene is located in a middle between the Fermi level of Al:Li and the LUMO of BP3T. Moreover, pentacene is known as a semiconductor with high carrier density. Employing this high conductance material with the moderate LOMO energy as the electron injection layer improves the charge injection property due to the decrease of contact resistance.[10–12] This improvement owing to the pentacene layer was also confirmed by observing the linear region of the static characteristics, as shown in Fig. 4. From these plots the electron currents were increased by inserting the pentacene layer, indicating the decrease of total resistance which is a sum of contact resistance and channel resistance. In this experiment the decrease of contact resistance by the pentacene layer contributes to the increased current because the channel resistance is equal.

In summary, ambipolar OLEFETs were fabricated with all vapor-deposited thin films of small molecules. The BP3T-based OLEFET with the buffer layer of *n*-triacontane and the electron injection layer of pentacene exhibited excellent ambipolar carrier transport properties, resulting in the gate-controlled wide emission zone within the channel region. In particular, this improved performance is attributed to the well-matched LUMO energy of pentacene positioned between the LUMO of BP3T and the Al:Li Fermi level.

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