

Ambipolar field effect transistors with heterojunction of organic semiconductors

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Abstract

Ambipolar operations in organic field effect transistors (OFETs) with heterojunction structures have been demonstrated. We have selected a biphenyl capped thiophene oligomer (BP2T) as p-type and fullerene (C₆₀) as n-type materials in the active layer of the OFETs. To investigate their intrinsic behaviors we measured the OFET characteristics in vacuum without breaking vacuum after device fabrication. Their electric characteristics depended on the heterostructure configurations. The OFET prepared with a co-deposited thin film of BP2T/C₆₀ showed high carrier transport performance and both carriers were efficiently injected into the channel of the active layer. In the bi-layered device, ambipolar characteristics were only observed when the n-type C₆₀ molecules penetrated deeply into the BP2T layer.

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1. Introduction

Organic semiconductors have *potentials* in application for active electronic devices due to their attractive advantages such as low cost, structural flexibility, and low temperature processing. There have been a lot of reports in the organic optoelectronic devices such as organic light emitting diodes (OLEDs) [1,2], solar cells [3], and field effect transistors (FETs) [4,5]. In the field of organic FETs (OFETs), significant progress has been achieved in the past few years. Transistors based on pentacene polycrystalline thin films have demonstrated a comparable performance to that of amorphous Si transistors [6]. Pentacene, one of the most widely studied p-type semiconductor, shows excellent conducting characteristics in OFET, and will be a leading candidate for industrial applications such as radio frequency identification tags, low-cost data storages, and switching devices for OLEDs and paper displays [7]. Most OFETs with a single component of

organic semiconductor reported so far show unipolar characteristics. On the other hand, ambipolar operation is indispensable to achieve practical applications to light emitting transistors and complimentary circuits [8]. For the ambipolar operation, it is important to select proper source and drain electrodes that allow efficient injection of electrons and holes in the highest occupied and lowest unoccupied molecular orbitals (HOMO and LUMO) of the organic semiconductor, respectively. There has been difficulty in choosing an appropriate electrode material for the electron and hole injections due to a wide gap of the HOMO and LUMO levels of organic semiconducting molecules [9]. Cua et al. demonstrated the ambipolar operation in an active layer of an organic semiconductor by passivating the SiO₂ layer [10]. There have been a few reports on OFETs where both carriers are transported in an active layer of organic thin films [11,12], and these devices were fabricated under a limited processing environment [13–15]. From this point of view, recently ambipolar organic field effect transistors (AOFETs) have been demonstrated for heterostructure devices using both p-type and n-type organic materials [13,16–20]. In those heterostructures, the organic active layer is composed of co-evaporated thin films or bi-layer structures (organic layers are successively built up).

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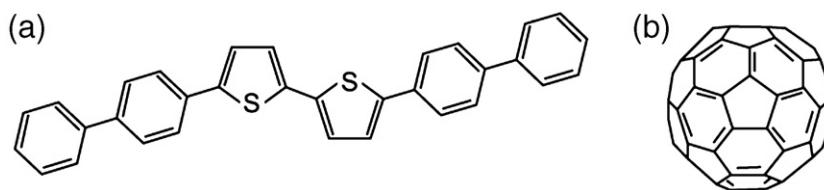


Fig. 1. Molecular structures of BP2T (a) and C₆₀ (b).

In this study we have focused on dependence of the carrier transport characteristics on the heterostructure of AOFETs using biphenyl-capped thiophene oligomers and fullerene (C₆₀) as p and n-type organic semiconductors, respectively.

2. Experimental details

Fig. 1 shows the molecular structures of 5,5'-bis(4-biphenyl)-2,2'-bithiophene (BP2T) and C₆₀. BP2T, which is known as a p-type material [21,22], was synthesized according to the published procedure [23]. The C₆₀ sample (99%) was purchased from Tokyo Kasei Kogyo Co., Ltd. Fig. 2 shows the structures of heterojunction OFETs fabricated using BP2T and C₆₀. In the bulk heterojunction structure (Fig. 2 (I)), the organic layer is composed of a 60 nm-thick co-evaporated thin film of BP2T and C₆₀ (1:1 weight ratio). In the bi-layer structure the 60 nm-thick first organic layer was deposited on a SiO₂/Si substrate, and then the second 60 nm-thick organic layer was successively evaporated, as shown in Fig. 2 (II) and (III). Using a system shown in Fig. 3 the heterostructure devices were fabricated and measured *in-situ*. A doped p-type Si wafer (20–30 Ωcm) with an insulating 400 nm-thick SiO₂ was used as the gate electrode. The organic active layer was deposited on it kept at room temperature under monitoring the evaporation rates by a quartz crystal microbalance. The deposition rate of all organic layers was kept at 1.7 nm/min. Then source and drain electrodes were patterned by deposition through a shadow mask to make the channel width (*W*) of 2 mm and length (*L*) of 200 μm. After fabrication of the OFET devices, they were transferred to the measurement chamber without breaking vacuum. Their FET characteristics were measured using a KEITHLEY model 4200 semiconductor characterization system at room temperature. All experimental processes were carried out in a vacuum less than 5 × 10^{−4} Pa. Morphology of the deposited organic layers was examined by atomic force microscopy (AFM) with an

alternating current (AC) mode with an Si₃Ni₄ cantilever using a JEOL JSPM-4200 scanning probe microscope.

3. Results and discussion

We first investigated FET characteristics of single layer films of C₆₀ and BP2T to elucidate their unipolar carrier transport behaviors. The carrier mobilities (*μ*) in the saturation regime were estimated using following equation.

$$I_{D(\text{sat})} = (WC_i\mu)/(2L)(V_G - V_{TH})^2. \quad (1)$$

Here, *C_i* is the capacitance of gate dielectric per unit area (7.5 nFcm^{−2}), *W* is the channel width, *L* is the channel length, and *V_{TH}* is the threshold voltage. The C₆₀ single-layer FET showed an electron mobility of 0.26 cm²V^{−1}s^{−1} while the BP2T device showed a hole mobility of 2.09 × 10^{−2} cm²V^{−1}s^{−1}. Fig. 4 shows drain current (*I_D*) vs. source–drain voltage (*V_{DS}*) of the device with the bulk heterojunction structure (I). A typical AOFET operation was observed. Under application of negative gate voltages (*V_G*), holes were induced in the BP2T domains, and then a typical p-type FET behavior was observed at low *V_{DS}* and high *V_G*. In this regime only holes were conducted in the organic layer. When *V_{DS}* was negatively increased, steep increase of currents was observed without current saturation. This suggests that an n-channel is formed in the C₆₀ molecules by electron injection from the drain electrode. The OFET has some unintended currents. The static characteristics shows the offset current at *V_G* ≠ 0 and *V_{DS}* = 0. This is due to the parasitic current which is observed when the organic semiconductor layer is unpatterned. Fig. 5 shows the transfer characteristics of the OFET with the bulk heterojunction structure (I). The electron mobility (*μ_e*) and hole mobility (*μ_h*) estimated in the saturation regime were ca. 8 × 10^{−3} and 5 × 10^{−3} cm²V^{−1}s^{−1}, respectively. These values were less than that of the single layer structure.

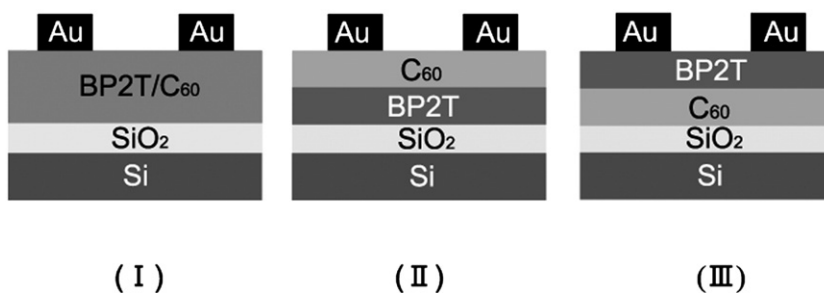


Fig. 2. Schematic diagrams of OFET devices with bulk heterojunction (I), bi-layer heterojunction structures (II) and (III).

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