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Depletion- and ambipolar-mode field-effect transistors based on the organic heterojunction composed of pentacene and hexadecafluorophtholocyaninatocopper

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ABSTRACT

We investigated heterojunction organic field-effect transistors (OFETs) using pentacene and hexadecafluorophtholocyaninatocopper ($F_{16}CuPc$) as double active layers. Two operation modes including depletion- and ambipolar-type were observed depending on the deposition order of two organic films. Depletion-mode was firstly observed from that devices with pentacene as the bottom layer and $F_{16}CuPc$ as the top layer, which was attributed to dipole effects originated from the pentacene/$F_{16}CuPc$ interface. Then improved device performances were obtained with mobility from 0.87 to 1.06 $cm^2/V\,s$, and threshold voltage shifted from −20 to +25 V as compared with conventional pentacene-based devices. Furthermore, the heterojunction OFETs exhibited typical ambipolar transport when alternating the deposition order of two films, which exhibited ambipolar mobilities with 0.06 $cm^2/V\,s$ for electron and 0.0025 $cm^2/V\,s$ for hole, respectively. All results implied the utilization of heterojunction can effectively improve the device performances of OFET, and operation mode strongly on the deposition order of two films.

1. Introduction

Organic field-effect transistors (OFETs) have been widely studied due to their potential applications in flat-panel display, low-end storage elements, sensors and complement circuits [1–4]. In past a few years, organic heterojunction has been introduced to OFETs in order to realize ambipolar devices [3,5–9]. The motivation of ambipolar OFETs is based on the necessity of simple fabrication complementary inverters like complementary metal-oxide-semiconductors (CMOS). It is well known that complementary technology will bring several advantages including better noise margin, lower power dissipation, and simplifying process [10]. One promised approach for achieving this goal is using ambipolar devices as fabricated elements. It is well known that ambipolar devices possess simultaneously both n- and p-type transport capability and thus reducing a step of patterning organic semiconductor, at the same time it can be operated for both positive and negative voltage unlike conventional unipolar devices that only operated for one polarity. However, the electric characteristics of ambipolar transistors are still worse than that of single-layer devices. Therefore, the studies on organic heterojunction are crucial for high-performance ambipolar OFETs.

Up till date, various process technologies for ambipolar OFETs have emerged by the combination of two organic components [11], the modification of metallic electrodes [12], using narrow band-gap materials [13], and utilizing organic heterojunction [6]. Among these methods, organic heterojunction is mostly popular for easily realizing ambipolar transportation. Actually, the first ambipolar OFET in the world was realized by employing organic heterojunction consisting of C60/6T in 1995 by Dodabalapur et al. [5]. Up till now, several organic heterojunction pairs have been reported including C_{60}/pentacene [7], CuPc/$F_{16}CuPc$ [8], BP2T/$F_{16}CuPc$ [9], PTCDI-$C_{13}H_{27}$/pentacene [14], PCBM/PPV [15], etc. The highest field-effect mobilities reached up to 0.23 $cm^2/V\,s$ for electron and 0.14 $cm^2/V\,s$ for hole based on C_{60}/pentacene heterostructure in inert ambient.

In this paper, the heterojunction OFETs consisting of n-type hexadecafluorophtholocyaninatocopper ($F_{16}CuPc$) and p-type pentacene have been studied for the following reasons. Pentacene, one of well-studied p-type semiconductor, shows the highest field-effect mobility [16] among all organic semiconductors. The n-type semiconductor, $F_{16}CuPc$, also shows high carrier mobility [17] and excellent stability in air, which offers enough flexibility for fabrication and measurement. Although pentacene and $F_{16}CuPc$ have different molecular shape and crystal packing manner (Fig. 1(a and b)), pentacene/$F_{16}CuPc$ heterojunction transistor can realize high device performances and typical ambipolar transport by proper deposition processes. OFETs with two operation modes

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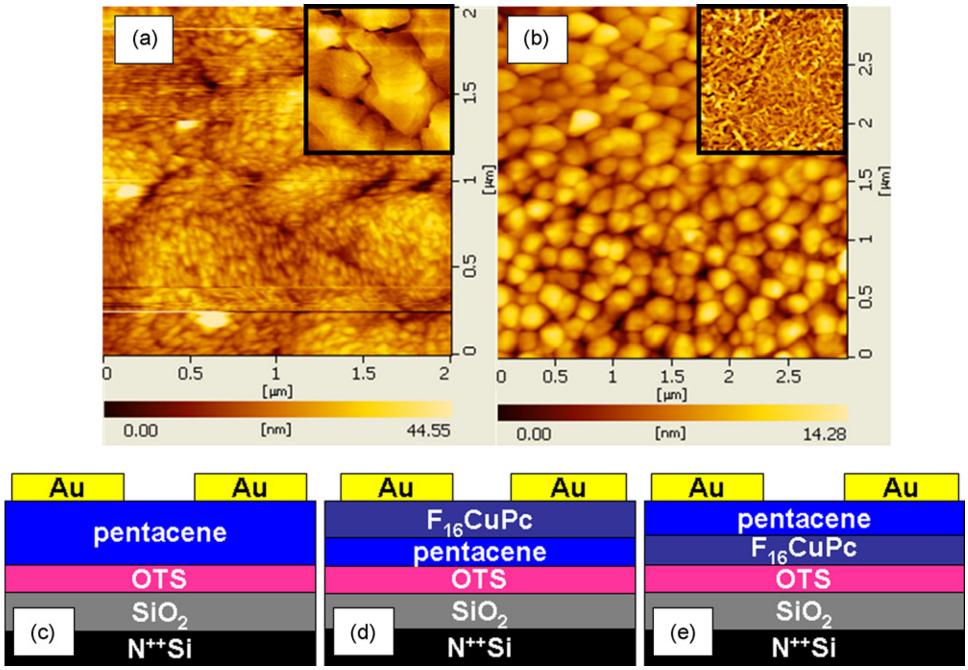

Fig. 1. AFM image (a) 15 nm F_{16}CuPc on 10 nm pentacene; (b) 15 nm pentacene on 7 nm F_{16}CuPc the inserts are pentacene (a) and F_{16}CuPc (b) on OTS/SiO_2; (c) schematic diagram of OFET with top contact based on pentacene as the active layers; (d) schematic diagram of OFET with top contact based on pentacene/F_{16}CuPc heterojunction as the active layers; (e) schematic diagram of OFET with top contact based on F_{16}CuPc/pentacene heterojunction as the active layers.

were demonstrated depending on the deposition order of two films that resulted in different interfaces for charge accumulation.

2. Experimental

Fig. 1(c–e) shows three structures of single-layer pentacene, pentacene/F_{16}CuPc, and F_{16}CuPc/pentacene heterojunction OFETs, respectively. All devices were fabricated on the substrate of heavily doped silicon wafers (0.01–0.015 Ω cm) served as gate electrode. A layer of oxide (SiO_2) covered on the substrate acted as gate insulator by thermal growth. Then, the SiO_2 was modified with octyltrichlorosilane (OTS) solution for the optimization of surface properties [18]. These wafers were immersed to OTS solution (chloroform as solvent, 2 mM) for 1 day and rinsed three times by solvent to remove aggregated OTS particles. The capacitance of SiO_2/OTS (8 nF/cm^2) was measured with an Agilent E 4980A *LCR* meter. The pentacene and/or F_{16}CuPc used as active layer were successively deposited onto the wafers by vacuum sublimation at a fixed rate of 0.1 nm/s (it is recorded by quartz oscillate) under background pressure of 10^{-4} Pa. At the same time substrate temperatures were set at 120 °C for F_{16}CuPc and 70 °C for pentacene film, respectively. All organic chemicals were purchased from Aldrich Company. Finally, 40 nm Au source/drain electrodes were deposited through shadow mask by thermal evaporation, where defined channel width (W) and length (L) was 3800 µm and 180 µm, respectively. Device performances were measured by Agilent 4155C semiconductor analyzer at room temperature in air ambient. The atomic force microscopy (AFM) images were performed by SPI 400 with tapping mode.

3. Results and discussion

We first investigated the electrical characteristics of pentacene/F_{16}CuPc heterojunction (pentacene as the bottom layer and F_{16}CuPc act as the top layer) transistor (Fig. 1(d)) in contrast to that of pentacene-based single-layer device (Fig. 1(c)). Typical output curves of the pentacene/F_{16}CuPc heterojunction (pentacene (10 nm) and F_{16}CuPc (15 nm)) OFETs are shown in Fig. 2(a). The linear and saturation regions can be observed with the increase of drain-source voltage (V_D). It shows a typical p-channel field-effect transistor characteristic. For comparison, the output curves of pentacene single-layer device are also presented in Fig. 2(a). At $V_G = -50$ V and $V_D = -50$ V, the on-state current (I_{on}) is 265 µA for heterojunction transistor, and 50 µA for pentacene single-layer device, it implied that a five-fold increased current has been obtained. Furthermore, off-state current defined as $V_G = 0$ V, is about 10^{-12}–10^{-10} A for single-layer device, while 10^{-5} A for the heterojunction device that meant depletion operation mode has been exhibited.

The field-effect mobilities and threshold voltage were extracted from saturation region based on the transfer curves using the follow equation:

$$I_D = \frac{W}{2L} C_i \mu (V_G - V_T)^2 \tag{1}$$

where W and L are the width and length of the channel, C_i is the capacitance of the gate insulator; μ is the field-effect mobility, and V_T is the threshold voltage. Fig. 2(b) shows the transfer characteristics of pentacene/F_{16}CuPc heterojunction transistor and pentacene single-layer device. The V_G are applied from +100 to −50 V with a fixed V_D of −50 V. The depletion and accumulation processes of hole may be found by scanning V_G from positive to negative value. The field-effect mobility of pentacene/F_{16}CuPc heterojunction OFET extracted from Fig. 2(b) is 1.06 cm^2/V s, which is higher than that of pentacene single-layer device (0.87 cm^2/V s). This indicates that the introduction of heterojunction can enhance effectively charge injection efficiency. In addition, a large shift of threshold voltage is observed from −20 to +25 V, which implies that operation mode has been transformed from accumulation-mode for single-layer OFET to depletion-mode for pentacene/F_{16}CuPc heterojunction transistor. Therefore it can be deduced that the conductive channel has been formed in heterojunction transis-