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Highly photosensitive thienoacene single crystal microplate transistors via optimized dielectric

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ABSTRACT

High photosensitivity and high photocurrent gain have been obtained based on dielectric optimized dinaphtho[3,4-d:3′,4′-d′]benzo[1,2-b:4,5-b′]dithiophene (Ph5T2) single crystal microplate transistors. In our experiments, the PMMA dielectric device shows the best operational stability without hysteresis effect. Based on such an optimized device, the photoelectric properties of the Ph5T2 single crystal microplates have been studied for the first time. The Ph5T2 phototransistor has the high photosensitivity at 21 mA W^{-1} and the extremely high photocurrent gain (I_{light}/I_{dark}) at 6.8×10^5. The photocurrent gain is higher than that of the most reported organic phototransistors (OPTs), and is in a class with the highest photocurrent gain for the reported values so far. This confirms that Ph5T2 is a photosensitive material and shows it promising potential in photoswitches and phototransistors.

1. Introduction

Organic phototransistors (OPTs) have attracted many researchers' attention recently because they combine the advantages of organic semiconductors and phototransistors [1]. Phototransistor is a three-terminal optoelectronic device with light-induced electronic signal modulation [1b]. It is capable to combine light detection, switching and signal magnification in a single device. Compared with the photodiode, the phototransistor has much higher sensitivity and lower noise [2]. Organic semiconductors offer many merits which include light weight, low processing temperature, large-area coverage, mechanical flexibility, low cost and incorporation of functionality by molecular design [3]. Combined with these advantages, OPTs can be applied into high-speed photodetectors and integrated circuits [2,4].

The excellent stability of organic field-effect transistors (OFETs) is a basic premise for their practical applications as OPTs. Currently, most studies on OFETs have focused on the optimization of mobility which indicates the ability of carrier migration and determines the switching speed of devices. A large variety of methods, for example, molecular configuration design, single crystal growth and interface modification, have been used to improve the mobility of OFETs [5]. However, the improvement of the device stability is generally neglected. Long-term environmental stability and operational stability remain two major issues that need to be resolved for OFETs [6]. The environmental and operational stability are related with many factors, which include material stability, dipolar orientation, charge trapping/detrapping events at all its critical interfaces and in the bulk of the semiconductor and gate dielectric [7]. It is desirable to obtain the OFETs with high mobility and good stability for further applications in optoelectronics.

In this communication, we selected the high air-stability thienoacene-based semiconductor, dinaphtho[3,4-d:3′,4′-d′]benzo[1,2-b:4,5-b′]dithiophene (Ph5T2), as the

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semiconductor layer to fabricate the single crystal OFETs (the molecular structure is shown in Fig. 1). This new material comprises of seven fused rings, two α-position fused naphthyl terminals and a benzene-thiophene alternating central unit. The low-lying HOMO energy level (−5.85 eV) determines its good environmental stability [8]. Its polycrystalline film device has exhibited the excellent thermal stability with a decomposition temperature of 427 °C [9]. Here, its single crystal microplates were fabricated by a physical vapor transport method. The highly ordered structure and the absence of grain boundary defects in organic single crystals are favorable for exploring the intrinsic charge-transport mechanism and obtaining the upper limit of the performance [10]. Three different insulators, SiO_2, octadecyltrichlorosilane (OTS) modified SiO_2 and poly(-methylmethacrylate) (PMMA), have been employed as the gate dielectrics to optimize the mobility and stability of Ph5T2 single crystal field-effect transistors (FETs). Based on the optimized FET, the photoelectric properties of the Ph5T2 single crystal microplates have been studied for the first time. The Ph5T2 phototransistors show a high photosensitivity of 21 mA W^{-1} and produce a photocurrent gain (I_{light}/I_{dark}) as high as 6.8×10^5, suggesting the potential applications of this material in organic optoelectronic device.

2. Experimental section

Preparation of Ph5T2 single crystals and instruments: Ph5T2 single crystal microplates were fabricated by a physical vapor transport method in a horizontal tube furnace. The purified Ph5T2 powders were used as raw material which was synthesized as described previously [9]. A quartz boat with the purified Ph5T2 powder was placed at the high-temperature zone and vaporized at 240 °C for 10 min. Si wafers were used as substrates which were loaded in the downstream of the horizontal tube furnace. The high-purity nitrogen (99.999%) was used as the carrier gas and the flowing rate was 20 ml/min. The system was evacuated by a mechanical pump with chamber pressure at 25 Pa during the whole growth process. The morphology of microplates and OFETs were obtained using field-emission scanning electron microscopy (SEM; Micro FEI Philips XL-30 ESEM FEG). Atomic force microscopy (AFM) measurements were carried out on a SPA400HV instrument with a SPI 3800 controller (Seiko Instruments).

Device fabrication and measurement: OFETs with bottom-gate top-contact configurations based on Ph5T2 microplates were fabricated by the "gold film stamping" method [11]. The main process of OFET device fabrication was carried out with a Cascade M150 probe station. Firstly, these Ph5T2 single crystal microplates were put onto substrates with the tip of the mechanical probe. Secondly, the high-tenacity and good-tractility Au layers were peeled off from the Si substrate with the tip of the mechanical probe and transferred onto the single crystal microplates as source/drain electrodes [12]. Three different gate dielectrics, SiO_2, OTS modified SiO_2 and PMMA have been used. The thickness of SiO_2 is 300 nm ($C_i = 10$ nF cm^{-2}). The Si/SiO_2 substrates were carefully cleaned and then treated with OTS to form a single molecular layer (SAM) [13]. Therefore, the C_i value of OTS modified SiO_2 is ~10 nF cm^{-2}. PMMA was dissolved in anisole and deposited by spin

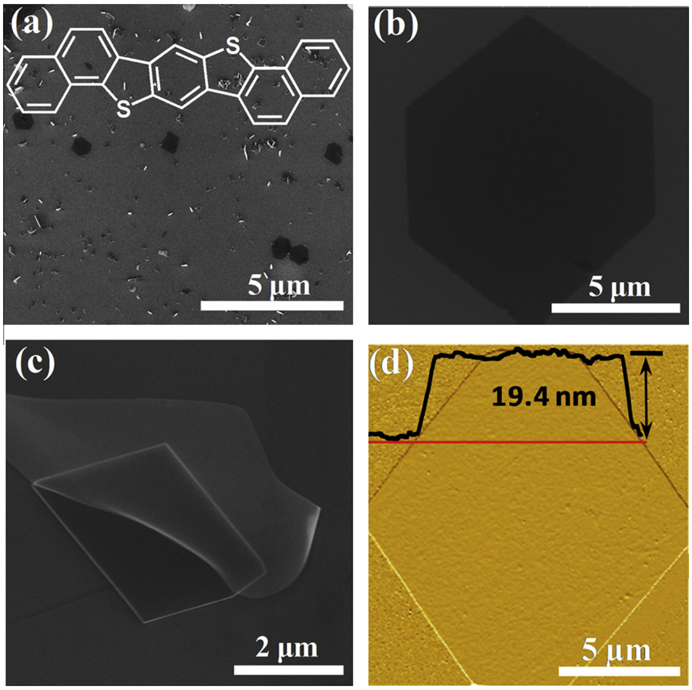

Fig. 1. SEM and AFM images of the Ph5T2 microplates. (a–c) Low and high-magnification SEM images. The inset is the chemical molecular structure of Ph5T2. The microplate is thin so that it stands on the substrate with the bending morphology. (d) AFM image.