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Correlating optimal electrode buffer layer thickness with the surface roughness of the active layer in organic phototransistors

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ABSTRACT

Inserting a C60 buffer layer between Au source/drain electrodes and pentacene active layer has been proved to improve the performances of pentacene organic phototransistors (PENT-OPTs) in our previous study. Buffer layer certainly has an optimal thickness with which the modified device can achieve the best performance. Based on the surface morphology analysis of different thickness C60 buffer layer on pentacene film, we further optimized the thickness of C60 buffer layer for best performance of PENT-OPTs and investigated its physical origins. Studies on PENT-OPTs with different pentacene surface morphology realized by different substrate temperatures indicate that the optimal thickness of C60 buffer layer directly related to the surface roughness of pentacene active layer and it is found that the optimized buffer layer thickness increases with the roughness of pentacene layer. Besides, we found that the photogenerated current of OPTs increases with the increasing of gate electric bias and then gradually reach saturation. An approximate analytical expression for gate voltage dependence of the photogenerated current was derived and used to fit the experiment data. An important parameter, saturated photoresponsivity, was introduced for better comparing the performances of OPTs.

1. Introduction

Organic field-effect transistors (OFETs) are attracting considerable attention due to their potential applications in low cost and flexible organic integrated circuits [1–4]. Compared with photodiodes, organic phototransistor (OPT) as one of the OFETs family have excellent performance in low noise and high sensitivity, and they have been a novel research area in photodetector during the past few years [5–7].

The performance improvement of organic electronic devices through structural optimization has been one of the focuses of the researchers' attention besides organic molecular modification [8]. It has been proved that the performances of OFETs can be improved by inserted an appropriate buffer layer between source/drain (S/D) electrodes and active layer [2,3,9–12]. We also found that pentacene-OPT (PENT-OPTs)'s field-effect characteristics and photosensitivity properties could be improved by inserting a C60 buffer layer between Au source/drain electrodes and pentacene active layer in our previous work. The performance enhancements of C60-modified device were interpreted by lowering the total hole injection barrier and increasing the photo-exciton dissociation efficiency [13]. Just like the optimization of OFETs' channel layer thickness [14], theoretically, the performances of the modified devices can be further optimized by adjusting the C60 buffer layer thickness. We supposed that the surface roughness of the active layer may affect the growth of C60 films and further affect the modifying effects of buffer layer in modified devices. It has been shown that the surface morphology of film increases with the increasing of the substrate temperate during film deposited [15,16]. In other words, films with different surface roughness can be realized by deposited at different substrate temperate. Thus, in this study, we especially prepared two series samples of pentacene films deposited at two different substrate temperate ($T_{S,PENT}$)

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on the OTS (octadecyltrichlorosilane) – treat Si/SiO$_2$ substrate and used these sample to fabricate C60-modified devices with different thickness C60 buffer layer. The optimal C60 buffer layer thickness was obtained for each series of devices by comparing photosensitivity characteristics of modified-OPTs. We also demonstrated the relationships between the optimal electrode buffer layer thickness and the roughness of the active layer by atomic force microscopy (AFM).

Additionally, we further investigated on the optimal C60-modified device and found that the photogenerated currents (I_{ph}) of OPTs will increase with the increasing of gate electric bias and then gradually reach saturation. An approximate analytical expression for gate voltage (V_{gs}) dependence of I_{ph} was derived and used to fit the experiment data of the optimal device. At last, based on the analysis of the relationship between I_{ph} of OPTs and gate voltage, we introduced an important parameter, saturated photoresponsivity, which can be used for better comparing the performances of OPTs.

2. Experimental

The details of sample growth and the structure of PENT-OPTs modified with C60 buffer layer were described in our previous report [13]. Unlike the previous report, a longer channel length ~50 μm was chosen. Two series of PENT-OPTs at $T_{S,PENT}$ of 65 °C and 110 °C were fabricated, respectively, each has five samples with different C60 buffer layer thicknesses (5 nm, 10 nm, 20 nm, 30 nm, 40 nm). For the purpose of surface morphology analysis, samples with the structure of SiO$_2$/OTS/pentacene and SiO$_2$/OTS/pentacene/C60 were simultaneously completed during device fabrication. The field-effect characteristics and photoresponsivity were obtained under the same conditions as the previous experiment. AFM analysis was carried out in tapping mode using an Agilent 5500 AFM system.

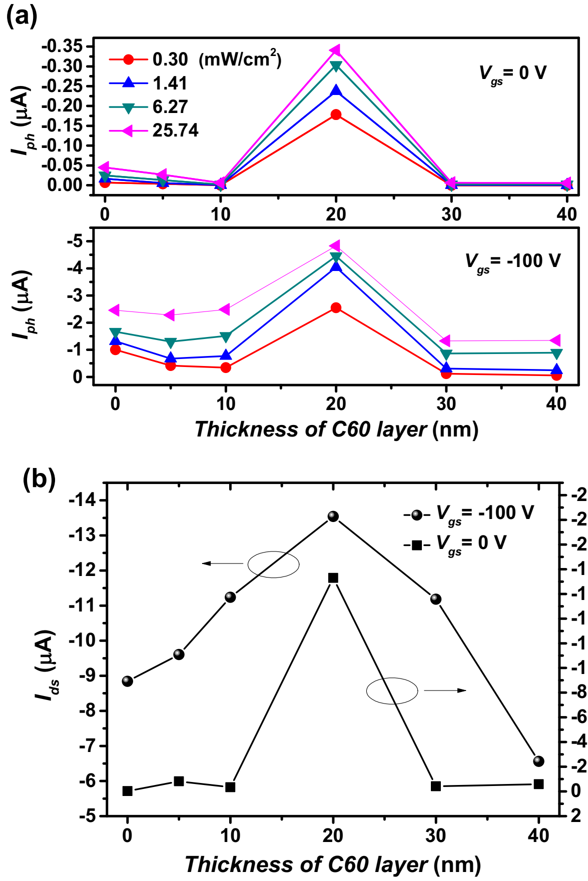

Fig. 1. (a) Plots of I_{ph} as a function of C60 layer thickness at V_{ds} = −50 V under different light intensities. (b) Plots of I_{dark} as a function of C60 layer thickness at V_{ds} = −50 V.

3. Results and discussion

The photogenerated current (I_{ph}) of OPTs is defined as the drain current difference between under light illumination (I_{ill}) and in the dark (I_{dark}) at the same gate and drain voltage. The dependence of I_{ph} on the C60 buffer layer thickness (d_{buffer}) of PENT-OPTs ($T_{S,PENT}$ = 65 °C) at V_{gs} = 0 V and −100 V are shown in Fig. 1a. It is obvious that the photosensitive characteristic of 20 nm-C60 modified device is superior over the other devices. It obtains 340 nA photogenerated current while PENT-OPT and other modified devices obtains less than 50 nA at zero gate voltage and light intensity (P_{opt}) of 25.74 mW/cm^2. Similarly, the 20 nm-C60 modified device obtains I_{ph} of 4.83 μA at V_{gs} −100 V, drain voltage (V_{ds}) of −50 V, which is apparently higher than that of the others. The relationship between I_{dark} and d_{buffer} at V_{gs} = 0 V and −100 V are shown in Fig. 1b, which is in accordance with the relationship between I_{ph} and d_{buffer}. Both I_{dark} and I_{ph} increase gradually when d_{buffer} is less than 20 nm. After I_{dark} reaching the peak value of 13.54 μA at V_{gs} = −100 V (d_{buffer} = 20 nm), Both I_{dark} and I_{ph} decrease, even less than that of PENT-OPT without buffer layers. These results indicated that PENT-OPTs ($T_{S,PENT}$ = 65 °C) with around 20 nm C60 buffer layer could obtain the best photosensitive characteristics.

As reported in the previous study [13], a thin C60 buffer layer inserted between gold S/D electrodes and pentacene layer could decrease the size of the interface dipole and reduce the hole-injection barrier; moreover, the heterojunction made of pentacene/C60 could effectively enhance the exciton-dissociation efficiency and hence increase I_{ph}. However, holes transfer in C60 layer is limited by the extremely weak hole-transport ability of C60; and a relatively high energy barrier for hole between Au and C60 further decreases the channel currents. We assumed that holes transportation is mainly through direct tunneling in Au-C60-pentacene structure which is in accordance with Park et al. [12] and Sun et al. [3]'s study on the similar OFET structures. The probability of tunneling injection is subject to the tunneling layer thickness, which may be one of the reasons why most of the modified devices' buffer layer are relatively thin, around 0.1–10 nm [2,3,10,12]. However, it can be inferred that the tunneling injection is strongly hindered when d_{buffer} exceeds 20 nm, for C60-modified devices in our study. In other words, the negative effects of 30–40 nm-C60 layer on tunneling injection become more significant than the positive effects of C60 electrode buffer layer: the reduction of the interface dipole and the enhancement of the exciton dissociation efficiency. So 30 & 40 nm-C60 modified devices exhibited poorer performances than the devices with 5–20 nm buffer layer, and even worse than PENT-OPT without buffer layer. Obviously, compared with most of the modified devices' buffer-layer thickness, 20 nm-C60 layer is still relatively thick. To explain why most of the excellent results appeared in the devices with such a buffer layer thickness, we further investigated the surface properties of pentacene and C60 thin-film by atomic force microscope (AFM).

AFM 2D images of 50 nm-pentacene thin film deposited on OTS-treat Si/SiO$_2$ are shown in Fig. 2. It can be seen that the pentacene grain size is around 200 nm, in agreement with previous observations [1,16]. In the case of pentacene deposited on OTS-treat Si/SiO$_2$ by conventional vacuum thermal evaporation, the average roughness of the prepared film surface was relatively larger and the root-mean-square (RMS) range of which was about 6–8 nm according to the different evaporation rates [4,17]. The maximum difference in height (peak-to-valley) obtained from inset of Fig. 2