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Research paper

Improving performance of OFET by tuning occurrence of charge transport based on pentacene interaction with SAM functionalized contacts

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ABSTRACT

Optimized pentacene thin film transistors have been achieved by two technological self-assembled monolayers (SAM) treatments, with surface modification of 3-octadecyltrichlorosilane (OTS) monolayer on SiO_2 dielectric layer and 2,3,4,5,6-pentafluorobenzenethiol (PFBT) monolayer on gold source/drain electrodes, respectively. Higher mobility and on/off ratio with 0.36 $cm^2 V^{-1} s^{-1}$ and > 10^6 are consistently investigated for films deposited on PFBT compared to on OTS, which could be explained by the different occurrence charge transport near the semiconductor/dielectric and semiconductor/electrodes interfaces. It can be further confirmed by XPS and electrical property measurements. In the end, a high mobility increased up to 0.68 $cm^2 V^{-1} s^{-1}$ was obtained by cumulative treatments of the two SAM. In particular, the improving performance of the organic thin films transistor devices through tuning the charge transport with SAM layers highlighting the utility of surface modulations and controlling of charge transport of interfaces in nanoscale materials.

1. Introduction

Organic field-effect-transistors (OFET) have been extensively studied in electronic applications due to its advanced advantages, such as low-cost, high integration, flexibility, and compatibility with biosensors [1–5]. However, commercial breakthrough is still ahead with considerable effort in fundamental improved as well as applied research currently undertaken. All these devices have in common organic semiconductor layers with processing a non-vanishing energy gap between occupied and empty electronic states, and must be inevitably realized with a range of metals because of the electrical connection of organic semiconductor to peripheral circuitry [6]. Thus it signifies to control the way of the charge transport between organic and metals. As we all know, the electrical performance of OFET is often measured in terms of the carrier field-effect mobility [7]. The carrier mobility is correlated with the charge transport performance in the dielectric/organic semiconductor device, which could be closely connected with the surface treatment, temperature, material purity, device structure, deposition vacuum conditions and so on [8]. Hence, it's also motivated to tuning the way of charge transport between organic and dielectrics.

During recent decades, an important approach of tuning charge transport is proposed by inserting self-assemble monolayers (SAM) on the surface of dielectrics or electrodes [9–12]. Charge transport takes place primarily within the first few monolayers at the dielectric/semiconductor [10]. For instance, the hydrophobic nature of 3-octadecyltrichlorosilane (OTS) has been widely used to modify the SiO_2 dielectric surface, results in improvement of the mobility of varies OFET, which could be explained by the increase of the semiconductor crystallinity, reducing interfacial trap states and planarize the surface [13–15]. And a number of thiol-based SAM such as 1-hexadecanethiol [13], 4-fluorothiophenol, and 2,3,4,5,6-pentafluorobenzenethiol (PFBT) [16,17], deposited on the source and drain electrodes of OFET have demonstrated improvements to the contact resistance and channel transistor performance. Very recently, Tomoharu Kimura et al. [17] directly investigated the local impedance and the potential difference at the electrode-channel interfaces of the OFET using frequency modulation scanning impedance microscopy (FM-SIM) presumed the reduction of the hole trap sites at the source-channel interfaces by using PFBT-modified OFET. Nevertheless, the hybrid contacts with both SAM on electrodes and dielectrics are rarely reported, especially the way for explaining the charge transport mechanisms in the two kinds of SAM contacts is expected to explore.

In this paper, the performances of different SAM modified pentacene FET devices were reported and compared, i.e. the FET of pentacene on bare SiO_2, the OTS modified pentacene FET, the PFBT modified pentacene FET, and both the two SAM modified pentacene FET. Pentacene was selected as the semiconductor in this paper because it is one of the most widely studied organic semiconductors in both

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academia and industry, and therefore severs as a good point of reference [18, 19, 20]. Otherwise, we used SiO_2 as the gate insulating layer, since it serving as a dielectric in numerous devices that can also be a preferential masking layer in many steps during device fabrication. The SiO_2 layer was grown by thermal oxidation that could obtain extremely high electrical quality of both film and interface, which is a key element on which has been built the success of modern OTFT technology [21,22]. Optimized electrical performances were obtained and the charge transport mechanisms were discussed, which highlights the utility of surface modulations to tune charge transport in nanoscale materials.

2. Experimental

In this work, the N-type negative Si (doped by Ph, 380–400 μm thick, resistivity of 0.0001–0.0003 Ω·cm) with 200 nm thick dielectric layer of SiO_2 were used as the substrates for all the samples. The substrates were cleaned by sonication in sequential baths of acetone, and isopropanol for 10 min each, dried by blowing N_2 gas (99.9% purity) at room temperature, and followed with putting them in ultra-violet zone for 25 min. The bottom contact of gold source and drain electrodes were fabricated by e-beam lithography with channel length from 1 μm to 50 μm and width 1000 μm, respectively. Surface structures of PFBT SAM and 3-octadecyltrichlorosilane OTS SAM were prepared by immersing in the solutions of PFBT mixed in ethanol with a ratio 1:10 and OTS mixed in clochroform with a ratio 1:10 for 18 h and 2 h, respectively. After fabricating the SAM, the samples were deposited with 30 nm thick organic semiconductor of pentacene by using a thermal evaporator at a deposition rate of 0.1 Å/s under 2×10^{-6} Torr at room temperature. A sample of pentacene transistor without any SAM treatments was fabricated as a reference. During the analysis, the AFM is used to analyze the thin film surface morphology. The modification of dielectric SiO_2 with OTS and Au electrodes with PFBT as well as on the deposited semiconductor pentacene thin films are analyzed by x-ray photoelectron spectroscopy (XPS) and UV-photoelectron spectroscopy (UPS). The electrical performances are operated in the N_2 glove box by using the Agilent 4156 C Semiconductor Measurement Unit SMU.

3. Results and discussion

The configuration of pentacene OFET device with both OTS and PFBT SAM modified surfaces is shown in Fig. 1(a). To compare the different SAM-modified gate dielectric layers in terms of the surface energy, the static contact angles were measured. As a result, the clean, bare sample without any SAM modification (bare SiO_2 and bare gold electrodes) typically had contact angles between between 65° and 72°. In further, the contact angles of the sample with both OTS and PFBT SAM modified surfaces measured between 95° and 105°, shown in Fig. 1(b) and (c). Indicating that the surface energy of OTS-treated SiO_2 is quite lower than the bare SiO_2, which is beneficial to deposit high quality of pentacene thin films [23]. The PFBT modified gold surface could change the work function of gold, consequently, decrease the contact resistance during the electric measurements, which would be discussed later. As the SAM could effectively influence the mo morphology of semiconductors, the 2d and 3d AFM morphologies of pentacene thin films deposited on bare surfaces and both OTS and PFBT SAM modified surfaces were carried out and compared, shown in Fig. 1(d) to (g). The pentacene deposited on bare gold electrode and bare SiO_2 shows a preferable bulk phase with a root mean square roughness (RMS) 10.5 nm on gold electrode area and 13.2 nm on SiO_2 dielectric, respectively. However, after the SAM modification on the surfaces, the pentacene shows a thin film phase with RMS decreased to 7.2 nm on PFBT modified gold electrodes areas and 9.5 nm on OTS modified SiO_2, respectively. The 50 nm thick pentacene thin films were measured by profilometry. Research from Bouchoms et al. [24] has verified that the pentacene could present a thin film phase and a bulk phase (triclinic in nature), and the device performance is believed to decrease once the film enters the bulk phase [25].

The drain current-gate voltage (I_{DS}-V_{GS}) transfer curves of different SAM modified OFET and the reference OFET (bare SiO_2) with channel length 2 μm and channel width 1000 μm are depicted in Fig. 2, where $\log I_{DS}$ and $I_{DS}{}^{1/2}$ is plotted versus V_{GS} at a fixed V_{DS} value of −40 V for all the samples. The mobility values of the transistors were calculated in saturation by using Eq. (1) based on Ihantola and Moll's [26] theory about isolated gate field effect transistor (IGFET).

$$I_{DS} = \left(\frac{W}{2L}\right) \cdot C_i \cdot \mu \cdot (V_{GS} - V_{Th})^2 \quad (1)$$

where C_i (insulator capacitance per unit area) $= \varepsilon_0 \varepsilon_{ox}/d_i$ (F cm^{-2}), W/L = channel width/channel length, μ = charge carrier mobility, V_{Th} = threshold voltage and V_{GS} = gate-source voltage.

As expected from the conventional OFET operation, the current flow through the OFET is strongly influenced by the gate voltage V_{GS}. All of the transfer characteristics of the OFET prepared here display a subthreshold regime between the switch on voltage and the threshold voltage. From the electrical transfer characteristics, the parameters of carrier mobility, threshold voltage, and subthreshold swing and on/off current ratio were extracted. The electrical performances were electrically characterized and determined in the saturation regime, the results of the different samples of OFET are summarized in Table 1 (every parameter was extracted by the average of 10 devices).

With the bare SiO_2 dielectric, the carrier mobility is only 0.03 cm^2 V^{-1} s^{-1} and the current on/off ratio is 10^4 orders of magnitudes. When the SiO_2 is treated with OTS monolayer, the carrier mobility increases to 0.048 cm^2 V^{-1} s^{-1} and current on/off ratio is 10^5orders of magnitudes, the optimized performance is consistent with

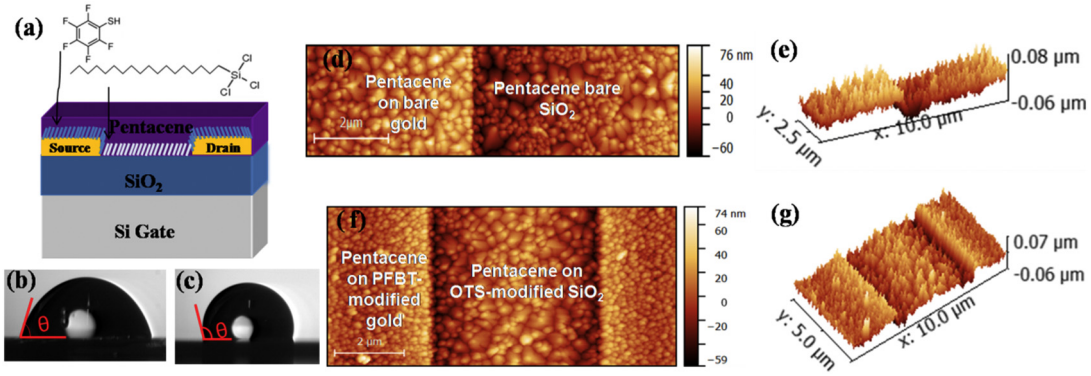

Fig. 1. (a) The configuration of pentacene OFET device with both OTS and PFBT SAM modified surfaces, (b) image of contact angle on bare surface, (c) image of contact angle on OTS and PFBT SAM modification, (d) AFM of the pentacene deposited on bare surface, (e) 3d AFM of image (d), (f) AFM of the pentacene deposited on OTS and PFBT SAM modified surfaces, (g) 3d AFM of image (f).