Effect of Side Chain Structure of Gate Insulator on Characteristics of Organic Thin Film Transistor

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Abstract

We propose a new method to achieve well-defined surface properties of the polymeric gate dielectrics without using SAM technique and inserting another organic/inorganic buffer layer. Pentacene thin film transistors(OTFTs) fabricated with the polyimide gate insulators with different side chain structures were demonstrated. Further, a relationship between the surface properties (surface morphology, surface energy, etc) of the films and the performance of OTFTs have investigated, which will be given in more detail in presentation.

1. Introduction

Considerable progress has been made on the pentacene thin-film transistor (OTFT) due to the simple processability, flexible controllability of chemical structure of the key materials. Relatively high performance OTFTs are made of a surface-modified inorganic gate insulator, such as silicon dioxide and silicon nitride. Many research revealed that the performance and stability of such OTFTs could be enhanced by modifying the surface of the inorganic gate insulator chemically and physically by covering the surface of a gate insulator with a standard hydrophobic primer, such as octadecyltrichlorosilane (OTS) and hexamethyldisilazane (HMDS), and a thin polymeric buffer layer[1,2] before the deposition of organic semiconductors, although the exact mechanism of device performance enhancement is still controversial.[3-10] The surface-modified gate insulator alters the interfacial properties between the organic semiconductor and the gate insulator and affects the initial growth mechanism of organic semiconductor.

Recently, we have reported a pentacene OTFT with polyimide gate insulator, however, still need to improve the device performance.[11-13] In this manuscript, we report a polyimide hybrid gate insulator with well-defined surface properties prepared by a hybridizing polyamic acid (P-B) with a specially designed polyimide (P-A), which has a non-polar octadecyl side chain, and investigate the effect of the existence of long alkyl chain of P-A on the device performance. For this study we have prepared two polymers: 1) P-A from DOCDA and DA18IM, and 2) P-B from CBDA and 4,4-diaminodiphenylmethane (MDA). A series of polymer hybrid was prepared from P-A and P-B varying hybridization ratio: (P-A/P-B, wt%): 0/100 (P-B), 2/98 (PI-H1), 5/95 (PI-H2), 10/90 (PI-H3). The chemical structures of the each monomers and hybrids are shown in Figure 1.
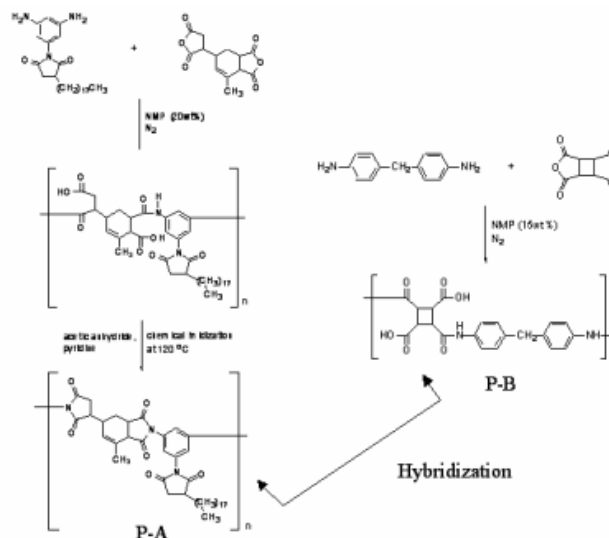

Figure 1. The chemical structures of the each monomers and hybrids.

2. Results

Atomic force microscopy (AFM) images (Digital Instrument Nanoscope IV, tapping mode) of the each hybrid film are shown in Figure 2. We observed a totally different surface morphology with increasing the content of P-A. Worm-like morphology, which is not observed in the film of P-B, starts to appear in PI-H1 and become much clearer in PI-H3. When P-B was hybridized with P-A, the surface of the hybrid film became more hydrophobic. This is confirmed by a contact angle measurement of water droplet on the hybrids and a calculated surface tension (from contact angle of water and diiodomethane) (PEONIX 300 contact angle analyzer). The measured contact angles were 64º, 80º, 81º, and 81º for P-B, PI-H1, PI-H2 and PI-H3, respectively. The calculated surface tensions of the hybrid films are 51.05, 39.06, 36.59, and 36.33 dyne/cm for P-B, PI-H1, PI-H2 and PI-H3, respectively. Interestingly, the water contact angle on the hybrids was dramatically increased and the corresponding surface tension was also dramatically reduced comparing with that of P-B itself. In addition, in separate pre-tilt angle measurement experiments[14], we found that the change of the surface wetting properties is possibly caused by the protruded long alkyl side chain of P-A. The electrical properties of the hybrids were also checked. They were determined by metal-insulator-metal (MIM) capacitor structure and found them to be suitable for the gate insulator application.
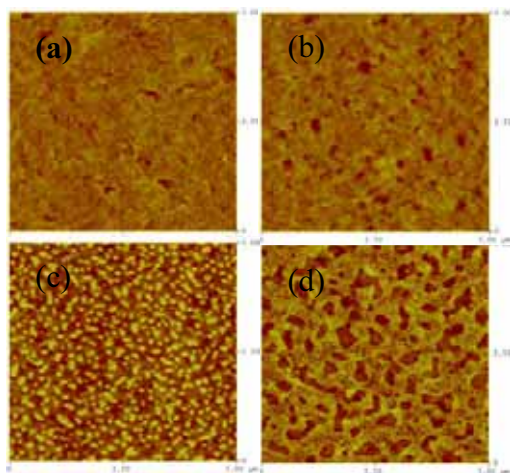

Figure 2. Atomic force microscopy images of the each hybrid film: (a) P-B, (b) PI-H1, (c) PI-H2, and (d) PI-H 3.

We have fabricated top-contact OTFTs with the hybrids.. Patterned indium tin oxide (ITO) on glass substrate was used as a gate electrode. The hybrid solution was spin-coated on top of the gate electrodes, and baked at 90 ℃ for 10 min on a hot plate in air. Subsequently, the pre-baked film was converted to the corresponding polyimide hybrid film by baking at 230℃ for 30 min on a hot plate in air at 250 °C for 1 min. The final thickness of the films was about 300 nm (KLA-Tencor α-step DC 50). A 60 nm-thick layer of pentacene was deposited on top of the gate insulator through a shadow mask by thermal evaporation at a pressure of 1×10^{-6} torr. The evaporation rate of the pentacene was 1 Å/s and the substrate temperature was 90 °C. The devices were then completed by thermally evaporating 50 nm-thick source and drain electrodes through a shadow mask. The electrical measurement was carried out in air without any encapsulation using an Agilent E5272 and HP 4294A.

Output characteristic curves (for drain current *vs* drain voltage, I_{ds} *vs* V_{ds}) of the pentacene OTFTs with the hybrid at various gate voltages and all OTFTs showed typical p-type characteristics with a clear transition from linear to saturation behavior (due to a pinch off of the accumulation layer). Figure 3 shows the transfer characteristic curve (for drain current *vs* gate voltage, I_{ds} *vs* V_{gs}) of all OTFTs, therein the performance parameters were extracted in a saturation regime. The field effect carrier mobility (μ) of pentacene OTFT with PI-H3 (0.47 cm^2/V·s) was higher than that of OTFT with P-B (0.07 cm^2/V·s) by more than 6 times. The subthreshold slope (*s.s.*) was also decreased significantly from 7.5 to 3.1 V/dec. Since the density of the trap at the interface between an organic gate insulator and an organic semiconductor is one of the factors influencing *s.s.*, this could be explained by the presence of traps at the interface.[15-17] The lowered *s.s.* indicates that modifying the surface of gate insulator to more pentacene growth-friendly surface results in lower density of trap at the interface.

When the hybrid (PI-H1~3), instead of nonhybrid one (P-B), is used as a gate insulator, the mobility

increases by up to six times, although the crystal size of pentacene film was reduced and barely exhibit dendritic structure. Considering only grain size of organic semiconductor, decreasing the grain size reduces the mobility. This conflicts with our result. However, the surface wetting properties of gate insulator adds another parameter, which dramatically alters the initial growth mechanism of pentacene.

The AFM images and XRD pattern of 60 nm-thick pentacene on the hybrid films revealed that pentacene on P-B film shows a dendritic structure and its grain size is around 0.5 ~ 1 μm and pentacene is highly ordered. The first peak at 5.71 ° (thin film phase) corresponds to a lattice parameter of 15.5 Å. However, the same thick (60 nm) pentacene film on other hybrid films (PI-H1~3) did not show any dendritic structure and its gain size was reduced significantly. Their main XRD peaks are from thin film phase, but a peak from bulk phase (6.1 °) was also observed (although the peak is very weak).
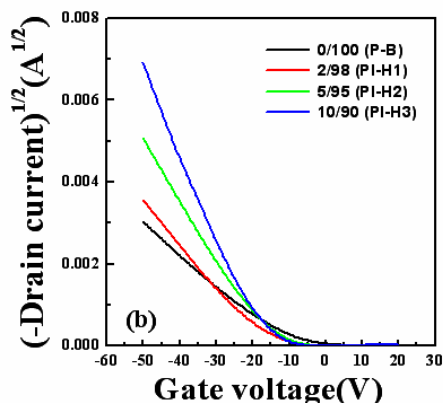

Figure 3. Transfer characteristic curves of the OTFT with the hybrids.

The appearance of peak at 6.1 ° on the hybrid film represents that some of pentacene molecules are more tilted to the surface of the hybrid film, and likely contribute into the increase of adhesion with the hybrid film. The increased adhesion likely gives a positive effect on the initial growth mechanism of pentacene and contributes to the improved mobility of OTFT. Considering that charge transport occur dominantly at a few pentacene monolayers, it is very important to control the surface properties of a gate insulator.

3. Conclusion
We found that the long alkyl chain protruding to the surface plays a major role in making the surface more hydrophobic and the monolayer influenced on the performance of OTFT dramatically. The long alkyl chain likely induces more flat-lying pentacene molecules and increases the adhesion between pentacene and gate insulator. This gives a positive effect on the initial growth of pentacene leading to the improvement of device performance. Unlike conventional surface modification technique, such as SAM treatment, this new approach using only single layer to engineer the surface property provide a new concept of the design of organic gate insulator.

5. References
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