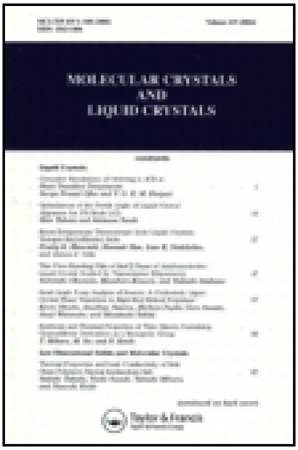

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Enhanced Electrical Properties of Organic Thin Film Transistors by the Pentacene Order on a Photo-Aligned Polymeric Insulator

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We report on the surface-induced molecular order and the optical anisotropy of a pentacene thin film on a photo-aligned polymeric gate insulator layer. Since a pentacene molecule has a rodlike shape, the induced orientational order of the pentacene molecules is expected on an alignment layer for liquid crystal molecules. The photo-aligned polymer insulator, exposed to a linearly polarized ultraviolet light, has a high cross-linked density and thus induces the structural order of the pentacene molecules. The pentacene thin film deposited on the photo-aligned polymeric insulator is found to show the optical anisotropy. The organic thin film transistor on the photo-aligned insulator exhibits good electrical properties.

Keywords: optical anisotropy; organic thin film transistors; pentacene film; photo-aligned polymeric insulator

INTRODUCTION

Since the first work on an organic transistor in 1986 [1], organic thin film transistors (OTFTs) have great progress for electronic applications such as an electronic paper, various sensors, and radio frequency identification cards [2–4]. Particularly, flexible display devices have

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become one of modern core technologies because they require a variety of flexible electronic circuits in future industry. Therefore, the OTFTs are expected to play a significant role in flexible displays. The overall performances of OTFTs are known to be inferior to those of amorphous silicon thin film transistors (a:Si-TFTs) despite of their wide potentials. The mobility of the pentacene was reported to be about 1 cm^2/Vs, which is comparable to a:Si [5]. Although such high mobility of the pentacene is often obtained on the SiO_2 layer as a gate insulator, SiO_2 requires high temperature and high vacuum to be processed. This means that SiO_2 will not be applicable for plastic substrates. Thus, studies on organic insulators have been carried out to find an alternative to the SiO_2. For the low temperature process, organic insulators such as poly-4-vinylphenol and poly-vinyl alcohol have been applied to flexible substrates [6,7].

Recently, the pentacene molecules on a surfactant treated surface were shown to increase the mobility of the pentacene in the OTFTs [8–10]. However, the basic mechanism for the mobility enhancement in relation to the surface induced ordering and the resultant surface morphology has not been studied so far.

In this work, we report on the surface-induced molecular ordering and the optical anisotropy in the pentacene thin film produced on a photo-aligned polymeric insulator layer. Upon the illumination of a linearly polarized ultraviolet (LPUV) light, the photo-aligned polymer used as a gate insulator is found to produce the optical anisotropy and a high cross-linked density. As a consequence, the pentacene film deposited on such treated polymeric insulator shows an optical anisotropy and high mobility in the OTFT.

EXPERIMENTAL

Figure 1 shows the device structure of a bottom gate, top contact OTFT. Glass was used as a substrate. Indium-tin-oxide (ITO) as a gate electrode was etched by the photo-lithography method to minimize the overlap between the gate electrode and the other two electrodes, the source and the drain. The ITO glass substrate was cleaned with acetone, iso-prophyl alcohol, methanol, and de-ionized water in sequence. The photopolymer of poly(vinyl cinnamate) (PVCi), dissolved in a cyclopentanone in 10 wt.%, was used as a gate insulator. PVCi was spin coated on the top of the ITO layer. It was baked below the boiling temperature of cyclopentanone, 130°C, on a hot plate for 5 h to completely remove any residual cyclopentanone. In order to produce an anisotropic anchoring force for aligning the pentacene molecules, the LPUV light was exposed to the photo-sensitive PVCi layer at

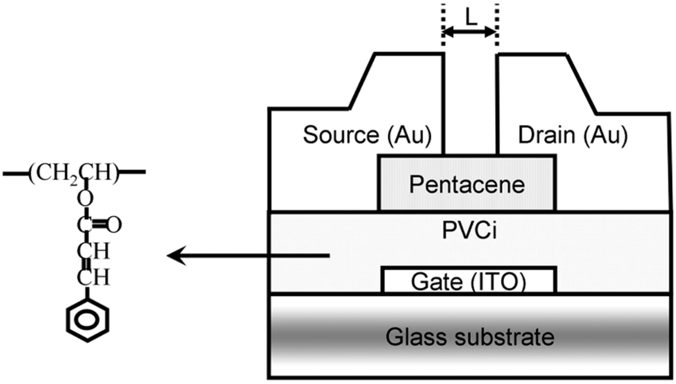


FIGURE 1 The device structure of a top contact OTFT and the molecular structure of PVCi as a gate insulator.

10 mW/cm^2 for 3 minutes. We used a broadband UV source of a high pressure Hg lamp for photo-aligning the PVCi. The pentacene film as an active semiconductor deposited onto the PVCi polymeric insulator layer through a shadow mask under a basal pressure of 10^{-6} Torr Torr at room temperature. The deposition rate was fixed at 0.5 Å/s. The thickness of the PVCi and that of the pentacene film were measured as 570 nm and 60 nm, respectively. Au was thermally deposited on the top of the pentacene film to prepare the source and the drain electrode through another shadow mask under 10^{-6} Torr. The deposition rate was 1.0 Å/s and the thickness of Au was 80 nm. The length and the width of the channel were 50 μm and 1 mm, respectively.

The optical anisotropy was measured with a photo-elastic modulator (PEM) [11]. The current voltage characteristics and the electrical properties of our OTFTs were measured using a semiconductor parameter analyzer (HP4155A) under the ambient pressure at room temperature.

RESULTS AND DISCUSSION

Figure 2 shows the experimental set up to measure the optical anisotropy of the pentacene thin film and the PVCi layer. Considering that the pentacene molecule has a rodlike shape, the surface order of the pentacene molecules would be induced on an alignment layer for the liquid crystal molecules through anisotropic surface anchoring. The orientationally ordered state of the pentacene molecules will produce a non-zero optical anisotropy. The phase retardation through

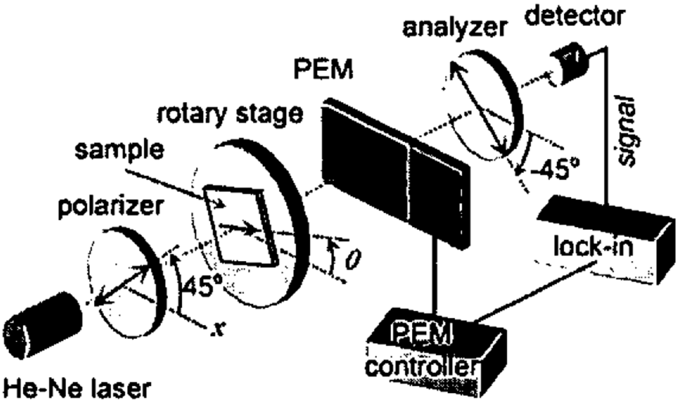


FIGURE 2 Experimental setup for measuring the optical anisotropy of the pentacene thin film deposited on the PVCi layer.

each pentacene film was measured using a phase retardation technique [12]. The azimuthal angle dependent phase retardation of the pentacene film was determined using the PEM (PEM-90, HINDS Instruments) set up.

In Figure 2, suppose that the time dependent phase retardation A by the PEM at the frequency Ω is $A_0 \cos(\Omega t)$, the maximum phase retardation of the sample is B_0, and the angle between the optic axis of the PEM and that of the sample is θ. The transmitted wave E is then expressed as

$$E = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ -1 \end{pmatrix} \frac{1}{\sqrt{2}}\begin{pmatrix} e^{u/2} & 0 \\ 0 & e^{-u/2} \end{pmatrix} R(\theta) \begin{pmatrix} e^{iB_0/2} & 0 \\ 0 & e^{-iB_0/2} \end{pmatrix} R(-\theta) \begin{pmatrix} 1 \\ 1 \end{pmatrix},$$

where $R(\theta)$ is the rotation matrix,

$$R(\theta) = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$$

The transmitted intensity I is given by [9]

$$\begin{aligned} I = I_{dc} &+ 8J_1(A_0)\sin B_0 \cos 2\theta \cos \Omega t \\ &+ 4J_2(A_0)[(1-\cos 4\theta) + \cos B_0(1+\cos 4\theta)]\cos 2\Omega t \\ &+ \text{high order terms}, \end{aligned}$$

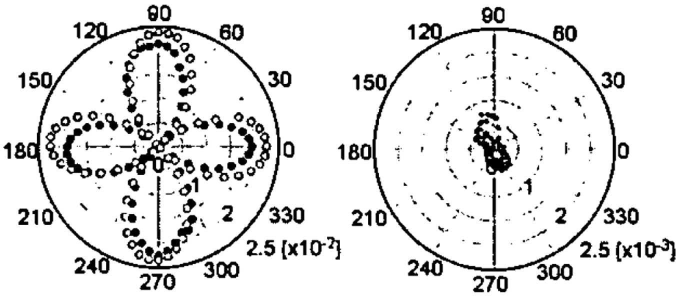
where J_1 and J_2 represent the first and the second orders of the Bessel function, respectively. I_{dc} represents the dc component of the transmitted intensity. Assuming that R_1 and R_2 are the first and the second harmonic terms dependent on θ, the maximum retardation B_0 is obtained for the case that $\theta = 0$,

$$B_0 = \tan^{-1}\left(\frac{J_2(A_0)R_1}{J_1(A_0)R_2}\right)$$

Figures 3(a) and 3(b) show the measured optical anisotropies of the pentacene films on the PVCi layer with no UV treatment and on the PVCi layer exposed to the LPUV light. The small and nearly isotropic phase retardation shown in Figure 3(a) suggests that no appreciable molecular ordering exists in the pentacene film on the non-treated PVCi layer. The pentacene molecules on the LPUV exposed PVCi layer, however, align themselves in a ordered state due to the anisotropic anchoring forces, and the resultant optical anisotropy is produced as shown in Figure 3(b).

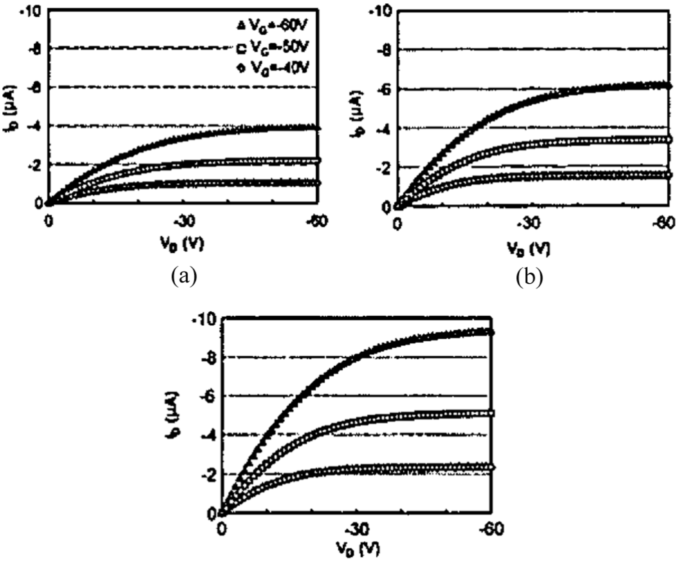
We now examine the output characteristic curves (I_D vs V_D) of three OTFTs fabricated under different surface treatments. The gate voltage was varied from 0 V to -60 V in a step of -10 V. As shown in Figure 4, the magnitude of the drain current (I_D) increases with increasing the LPUV exposure time, i.e., with aligning more and PVCi molecules. In the saturation region, the drain currents for the non-treated PVCi, the LPUV exposed PVCi for 30 sec, and the LPUV exposed PVCi for 3 min were found to be 4 μA, 6 μA, and 9 μA, respectively.

Figure 5 shows the transfer characteristic curves (I_D vs V_G) of our three OTFTs. The carrier mobility was calculated in the saturation



(a) (b)

FIGURE 3 The optical anisotropies of the pentacene thin films deposited on (a) the PVCi layer exposed the LPUV for 3 min and (b) the PVCi layer with UV non-treatment. The thickness of the PVCi layer and that of the pentacene thin film are 570 nm and 60 nm, respectively. Open and closed circles represent the pentacene film and the PVCi layer, respectively.



(a)

(b)

(c)

FIGURE 4 The output characteristic curves of the OTFTs with the different LPUV light exposure times, (a) no UV, (b) 30 sec, and (c) 3 min, respectively. Triangles, squares, and diamonds represent the applied gate voltage of −60 V, −50 V, and −40 V, respectively.

region as follows [13].

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

where L and W are the length and width of the channel, respectively. Here, C_i is the insulator capacitance per unit area, μ is the carrier mobility in the saturation region, V_G and V_T are the gate voltage and the threshold voltage, respectively. The mobility was determined at the drain voltage of −60 V. The mobilities of three OTFTs for the LPUV exposure time of 0 sec, 30 sec, and 3 min were measured as 0.0515 cm^2/Vs, 0.0822 cm^2/Vs, and 0.1147 cm^2/Vs, respectively. The mobility for the 3 min-LPUV exposure case is above two times larger than that for the non-exposure case. The current on-off ratio, $I_{\mathrm{ON}}/I_{\mathrm{OFF}}$, is about 10^5 and the threshold voltage V_T is about −20 V. The induced optical anisotropy of PVCi and the resultant molecular order of the pentacene molecules on the photo-aligned PVCi insulator layer plays a significant role in the electrical properties such as the carrier mobility in the OTFTs. The mobility enhancement comes from

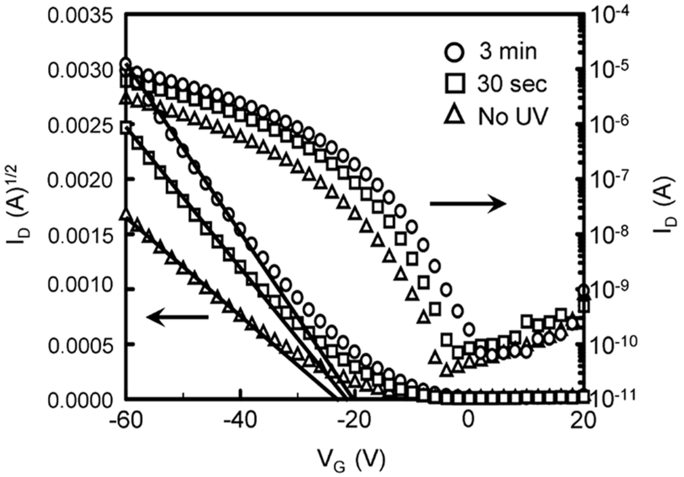


FIGURE 5 The transfer characteristic curves of the OTFTs shown in Figure 4. Open circles, squares, and triangles represent the LPUV exposure time of 3 min, 30 sec, and no UV, respectively. The drain voltage V_D is fixed at -60 V in calculating the mobility.

the increase in the photo cross-linked density of the PVCi insulator by the LPUV exposure.

CONCLUSION

We studied the optical anisotropy and the associated surface molecular order of the pentacene film on a photo-aligned polymeric insulator by the LPUV exposure. As the LPUV exposure time increases, the optical anisotropy of PVCi increases. The pentacene film deposited on such aligned PVCi layer shows a large optical anisotropy and has a more ordered state. The molecular order on the PVCi insulator is important to enhance the electrical properties of the OTFTs for potential applications of flexible electronic devices.

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