Molecular Aligning Properties of a Dielectric Layer of Polymer-Ceramic Nanocomposite for Organic Thin-Film Transistors

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Abstract

We investigated the molecular aligning capability of a polymer layer containing ceramic nanoparticles which can be used as a gate insulator of organic thin-film transistors (OTFTs). Because of the enhanced dielectric properties arising from the nanoparticles and molecular aligning properties of the polymer, the composite layer provides excellent mobility characteristics of the OTFTs.

Introduction

All organic displays (AOD) have received considerable attention since they are applicable for flexible displays and have the prospect of low-cost manufacturing. However, several barriers exist currently in the practical realization of the AOD such as relatively low reliability and device performances of organic thin-film-transistors (OTFTs) compared to silicon-based TFTs.[1] Two important problems that should be improved are low mobility of an active layer (organic semiconductor) and the high operating voltage. In order to achieve the high on-off ratio that represents the performance of the OTFTs, high mobility of the active layer is desirable.[2] In spite of demerits, such as the damage of the organic materials or high power consumption, the high operating voltage is necessary to compensate for the insufficiency of the transconductance $g_m=\mu C_{ox}\ (V_g-V_T)W/L$, where μ, C_{ox}, V_g, V_T , W/L are the mobility, the capacitance of insulator per unit area, the gate voltage, the threshold voltage ,and the ratio of the width to the length of the channel, respectively.[3] Moreover, with higher voltage, the higher charge density can be induced that causes localized traps to be filled. The localized trap is one of the factors that decrease the mobility. [4] [5]

There are two issues on solving the above problems. One concerns the organic material itself. An improvement in the purification process and the structural order of the organic semiconductor can be made increase the mobility.[6] The other approach concerns the insulator of the OTFTs. Because the mobility depends on the concentration of carriers accumulated in the channel in the OTFTs, the insulator should be thinner and its dielectric constant should be higher to induce a larger number of carriers at low voltage. [5]

In order to improve the mobility of the active layer , various researches have been carried out to increase the molecular ordering at interfaces which is one of factors related to the mobility characteristics of the OTFTs.

Especially, the molecular ordering of rod-like molecules such as pentacene can be increased by employing a liquid crystal (LC) alignment layer as a gate insulator.[7] As in the LC case, the alignment layer will induce the orientational ordering of the organic semiconductor molecules. However, common LC aligning materials have several limitations for use as gate insulators for the OTFTs mainly due to their intrinsically low dielectric properties compared to typical inorganic materials. Relatively low dielectric constant demands high operating voltage that causes undesirable effects.

In this work, we propose a composite-type insulator for the OTFTs, i.e., a polymer-ceramic nanocomposite. The polymer-ceramic nano composite is a hybrid material in which a polymer is physically mixed with ceramic nanoparticles.[8] It has a high-K dielectric constant and aligning properties due to high-K ceramic nanoparticles and the polymer which is used as the LC alignment layer. This dual-purpose technology would be useful for realizing the high-performance OTFTs.

Experimentals

As an organic LC aligning material in the organic-inorganic composite, nylon 6 (dielectric constant is 3.7 @ 1khz) was selected. Titanium oxide (TiO_2)(dielectric constant is 41 @ 1khz) was selected as an inorganic high dielectric material. The volume fraction of TiO_2 in nylon6 was 40%.

The dispersion of ceramic nanoparticles in polymer and the roughness of the polymer ceramic nanocomposite was investigated by the scanning electron microscope (SEM) and atomic force microscopy (AFM).

Experimental values of dielectric constants were obtained by an impedance analyzer. (HP4192A).

The phase retardation of a polarized light through the ordered structure in a thin film [9] was measured by a photo-elastic modulator. (Hinds PEM 90).

A thin film transistor fabricated is shown in Fig. 1. An aluminum gate electrode is deposited on a glass substrate. The insulating material (nylon6 or nylon6 TiO_2 composite) was then spin coated on the gate electrode (500rpm 5s, 100rpm 3s and 2000rpm 60s) and baked in an oven (60℃ 30 minute and 140℃ 1 hour). After the surface treatment on the insulator (mechanical rubbing or non treatment), pentacene was deposited on the insulator at 0.5Å/s. The thickness of the pentacene film was 60nm. The source and the drain was deposited at the rate of 1Å/s to reach 27nm. The current-voltage characteristics of the TFT were investigated by a semiconductor analyzer.

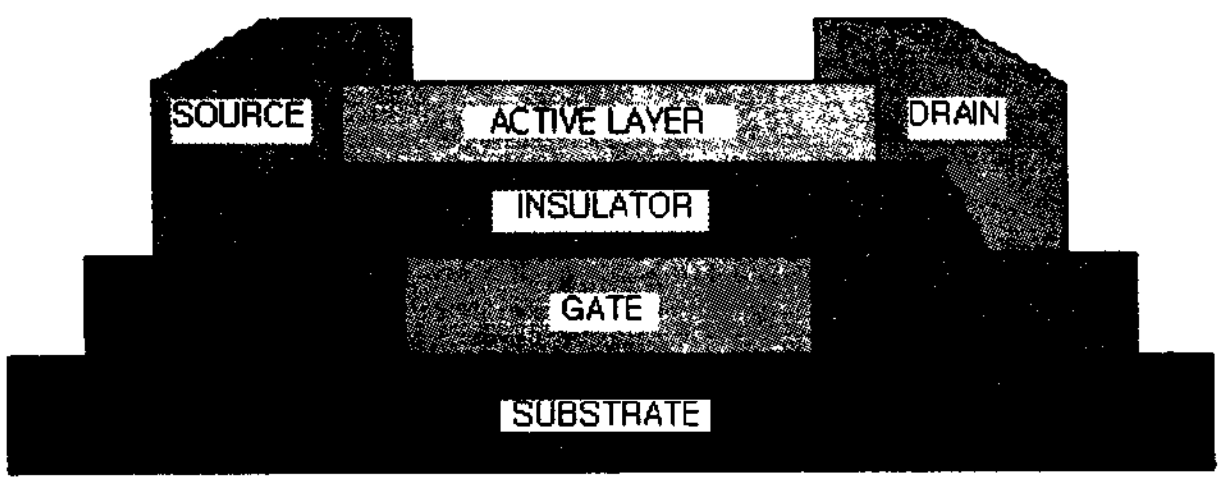
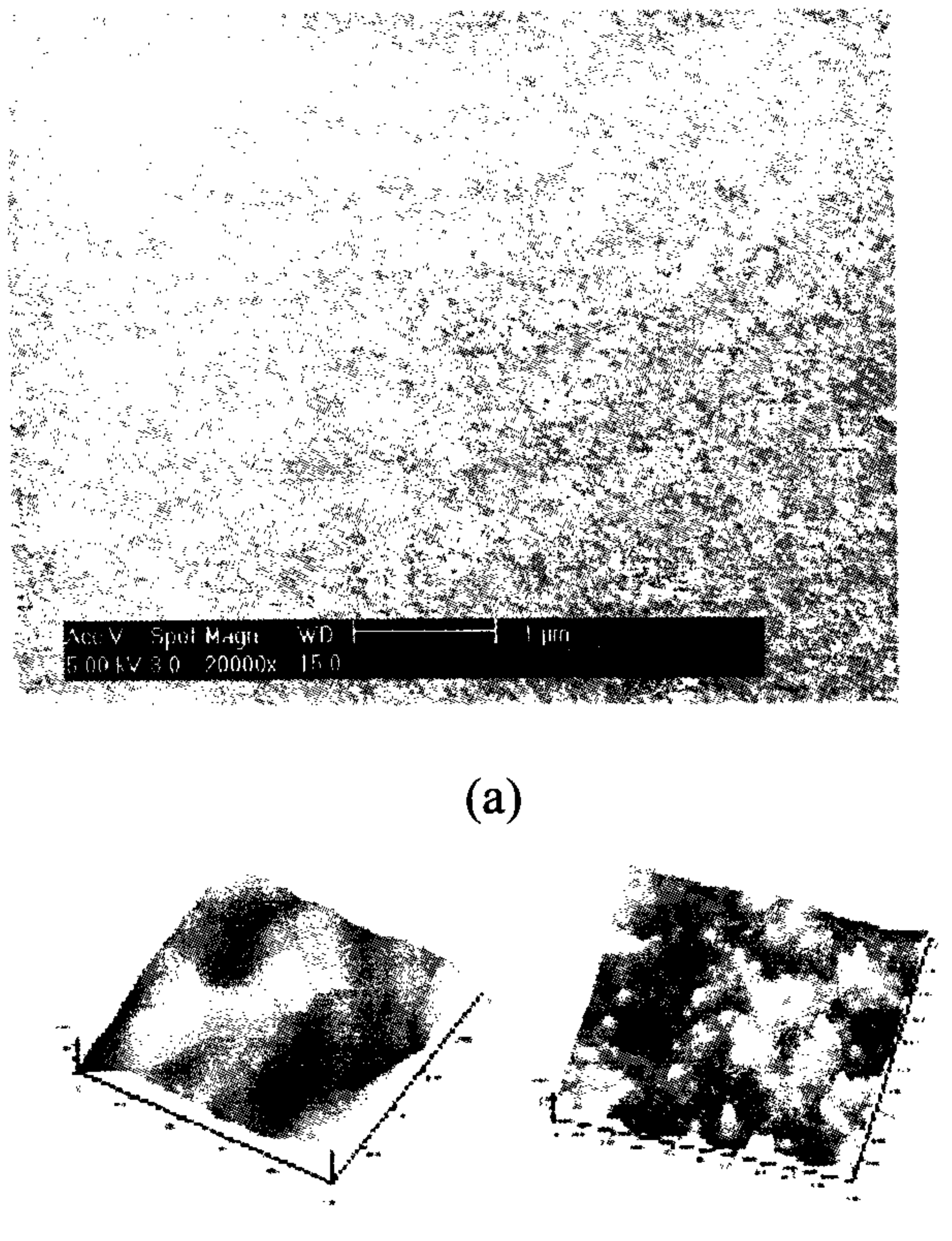


Fig. 1. The structure of the OTFTs being studied..

Result and discussion

Fig. 2. shows that ceramic nanoparticles were well dispersed in the polymer. The RMS roughness of nylon6 is 5.6nm~7.3nm and nylon6 TiO_2 composite is 3.7nm~4nm. The rubbing treatment of each layer enhanced the RMS roughness as 0.2nm~2nm. Although the surface roughness of nylon6 TiO_2 composite layer is lower than the nylon6 layer, the surface morphology of the nylon6 TiO_2 composite is sharper and the grain size is smaller.



(a)

(b) (c)

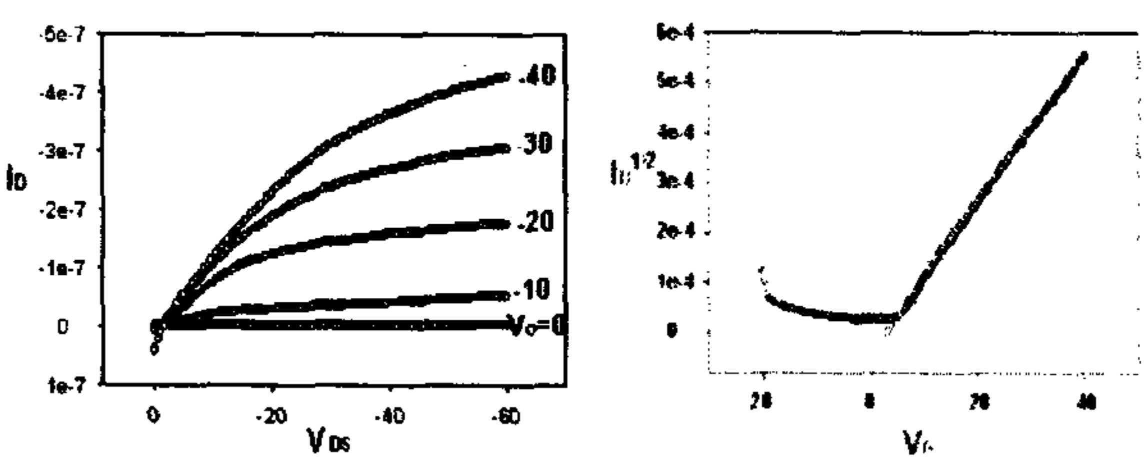
Fig. 2. (a)The SEM image of the nylon6 TiO_2 composite. White spots indicate the dispersed of TiO_2 nanoparticles. The AFM images of the nylon6 layer (b) and the nylon6 TiO_2 composite layer.(c).

Data of the phase retardation of a polarized light through pentacene films (deposited at the same condition maintained at manufacturing process of device) and the dielectric constants of the nylon6 and nylon6 TiO_2 composite are on in table 1. Table 1 shows that the TiO_2 particles enhance the dielectric constant of the alignment layer, however reduce the aligning property of pentacene.

Insulator / Property	Nylon 6 layer		Nylon 6 TiO_2 composite layer	
	Rubbed	**Non Rubbed**	**Rubbed**	**Non rubbed**
Phase retardation Through the pentacene film	0.012	0	0.006	0
Average mobility of the pentacene (cm^2/vs)	0.0040	0.0038	0.0043	0.0034
Dielectric constant of the insulator (@ 1KHZ)	4		14	
Capacitance per unit area of the Insulator	17.7nF/cm^2		29.5nF/cm^2	

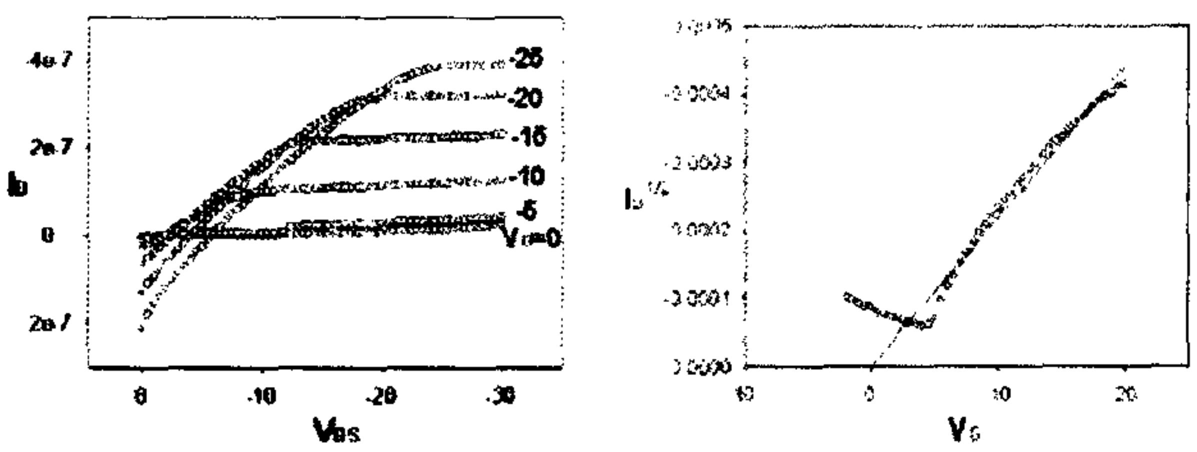
Table 1. Properties of insulators and pentacene film deposited on insulators.

The effects of the aligning property and the dielectric constants of the insulating layers on the OTFT performance are shown in Fig. 3. and 4.



(a) (b)

Fig. 3. (a) I_D versus V_{DS} characteristics for a OTFT with the composite insulator. (b) $I_D^{1/2}$ versus V_G characteristics for the OTFT of (a). The ratio of the channel length and the width was 5 and the drain voltage in (b) was biased as high as –30V.



(a) (b)

Fig. 4. (a) I_D versus V_{DS} characteristics for a OTFT with the composite insulator. (b) $I_D^{1/2}$ versus V_G characteristics for the OTFT of (a). The ratio of the channel length and the width was 5 and the drain voltage in (b) was biased as high as –20V.

The mobility can be calculated from the slope of the $I_D^{1/2}$ -V_G plot in the saturation regime, using the following equation [2]

$$I_D^{sat} = -\mu C_{ox}\frac{W}{L}(V_G - V_T)^2$$

where V_T is the threshold voltage. The average mobility of the OTFTs are presented in Table 2.

As shown in Fig. 3 and 4 the enhancement of the dielectric constant of the insulator reduces the operating gate voltage by 10V. Table 1 shows that the rubbing treatment of the insulator increases the average mobility of the OTFTs.

Considering that the main difference between the nylon6 insulator and the composite insulator is the capacitance, let us examine I_D versus V_{DS} characteristics for a OTFT with the composite insulator and a OTFT with the nylon 6 insulator for fixed capacitance(29.5nF/cm^2). We have used the following equation in the linear regime [2]

$$I_D^{linear} = -\mu C_{ox}\frac{W}{L}(V_G - V_T)V_{ds}\ .$$

As shown in Fig. 5 , the scaled current values of the OTFT with the composite insulator are similar to the OTFT with the nylon 6 insulator in the saturation regime. However, leakage current at high V_G (-20V) is larger than that of a low V_G (-10V). This large leakage current causes serious problems in the device performances.

In contrast to the OTFTs with the nylon 6 insulator, there exists other factors that disturb the electronic transport in the OTFTs with the composite insulator at low V_{DS}.(lower than −15V) The morphology of the surface of the insulator may be one of the factors. It has been shown that the current through the gate insulator is directly related to the interface roughness [10]. Such mechanism is supported by the AFM image of Fig. 2, because of its sharper and smaller grain sizes in the composite insulator.

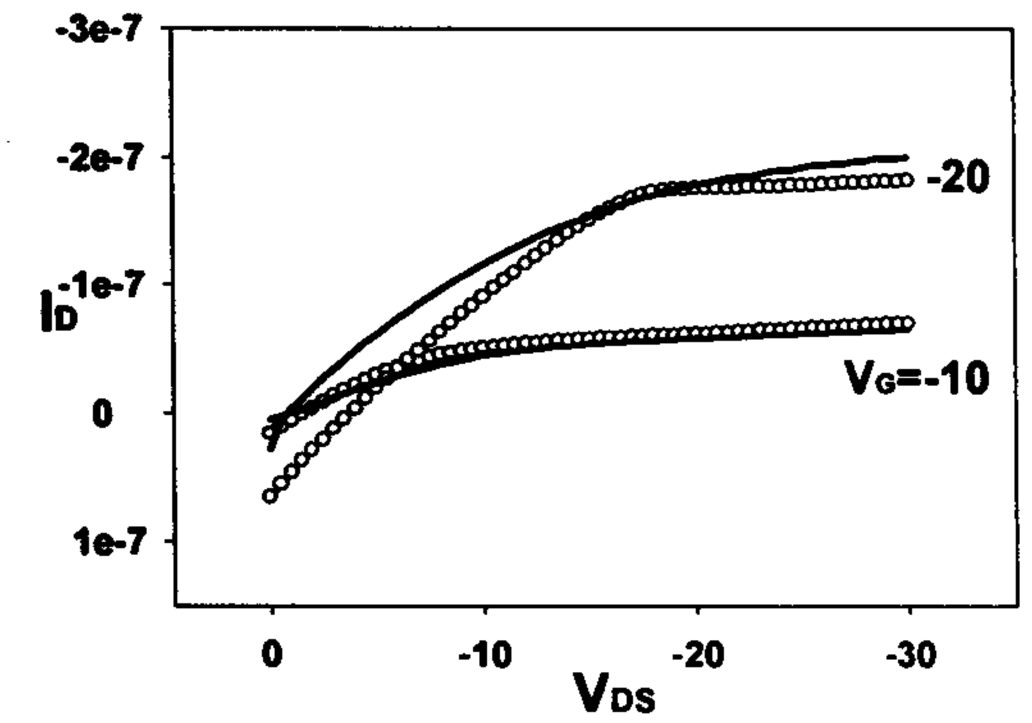


Fig. 5. Scaled I_D versus V_{DS} characteristics of OTFTs with nonrubbed composite insulator (circles) and of OTFTs with nonrubbed nylon 6 insulator.(solid lines)

Conclusion

We investigated the molecular aligning capability of the polymer layer containing ceramic nanoparticles which can be used as a gate insulator of the OTFTs. In the presence of the highly dielectric nanoparticles in the polymer layer, the dielectric properties of the composite polymer layer were remarkably enhanced. Moreover, the highly ordered structure of pentacene induced by such insulator layer provides excellent mobility characteristics of the OTFTs. This dual-purpose technology would be useful for realizing the OTFTs for high-performance applications. However, large leakage currents are produced in the OTFTs with the composite insulator. The surface morphology of the insulator may be one of the reasons that cause the large leakage current.

Acknowledgement

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