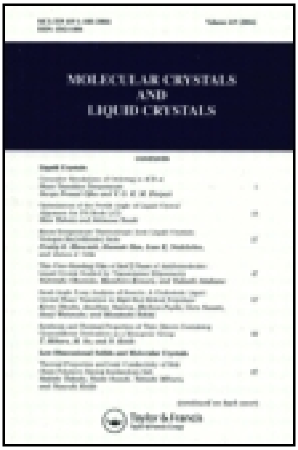

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ALL-POLYMER FET BASED ON SIMPLE PHOTOLITHOGRAPHIC MICRO-PATTERNING OF ELECTRICALLY CONDUCTING POLYMER

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We fabricated All-polymer FET (field effect transistor) whose substrate, insulating layer, active layer, and electrodes were composed of the organic polymeric materials. Active layer and all electrodes were made by the simple photolithographic micro-patterning of the electrically conducting poly(3,4-ethylenedioxythiophene). We figured out source-drain current (I_{SD}) of the FET decreased with increase of the positive gate voltage (V_G), implying the p-type FET worked in the depletion mode. Turn-off gate voltage, trans-conductance and on/off ratio were measured to be +30 V, −1.2 μA/V, and 10^4, respectively. We believe the All-polymer FET has significant advantages over other existing organic FETs since the device can be fabricated by the simple process at room temperature.

Keywords: electrically conducting polymer; poly(3,4-ethylenedioxythiophene); Photolithographic micro-patterning; field effect transistor; All-polymer FET

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1. INTRODUCTION

Recently, organic field effect transistor (OFET) has gathered great interests since OFET possesses many attractive advantages over the conventional inorganic FET such as mechanical flexibility, light weight, low processing temperature and low fabrication cost [1–3]. OFET, therefore, has been considered as a promising drive system for various devices requiring large area and mechanical flexibility, including active-matrix liquid-crystal display, active-matrix emissive display, active-matrix flat panel imager, smart card or large-area sensor array [4,5]. However, OFET composed of the small organic molecules requires complicated manufacturing processes because of poor film-forming property of the organic molecules. In the process, several cycles of lengthy pump-down must be included to evaporate each component of device at an elevated temperature [6]. Moreover, current leakage may take place in the OTFT due to the poor interface adhesion between the metal electrodes and the organic active layer.

Since electrically conducting polymers are known to possess excellent properties such as high electrical conductivity, ease of synthesis, good film-forming property, good mechanical flexibility, fairly high transparency, and good environmental stability at room temperature, they have been recently considered as the promising material for the electrodes as well as the active layer of OFET [7–11]. Nevertheless, micro- or submicro-patterning of the electrically conducting polymer film is still relatively complicated, which has limited practical application of electrically conducting polymers to the OFET.

In this study, we report an easy fabrication method of All-polymer FET whose substrate, insulating layer, electrodes, and active layer are all polymeric materials. The fabrication process was based on a simple photolithographic micro-patterning of electrically conducting polymer at room temperature as reported earlier [12]. We studied the electrical, optical, and morphological properties of the electrically conducting polymer thin film prepared by the method of this study. We also investigated the electrical characteristics of the All-polymer FET such as turn-off gate voltage, transconductance and on/off ratio. We believe the fabrication process of All-polymer FET reported in this study exhibits significant advantages over other existing methods.

2. EXPERIMENTAL

We used the simple photolithographic micro-patterning of electrically conducting polymer to fabricate the active layer and all electrodes of the

All-polymer FET. Micro-patterns of the electrically conducting polymer thin films were fabricated as following procedure. The oxidant film was first formed on a flexible and transparent PET or PP film substrate by spin-coating aqueous solution of various weight ratios of ferric p-toluenesulfonate (FTS) to PVA as the oxidant and the matrix polymer, respectively. The oxidant film was exposed to UV light (365 nm) with the intensity of 10 mW/cm^2 for 10 minutes through a photomask. Because Fe^{3+} in the oxidant is changed into Fe^{2+} upon UV irradiation, the oxidant in the exposed area can no longer oxidize the monomer. The patterned oxidant film was then exposed to 3,4-ethylenedioxythiophene (EDOT) vapor, resulting in polymerization of EDOT only on the unirradiated area.

Using the patterning method, we fabricated All-polymer FET with the structure as shown in Figure 1. FET was fabricated at room temperature as the following procedure. The rectangular gate electrode with a width of 1 mm and a thickness of 100 nm was first formed on a PET film by patterning of electrically conducting PEDOT. Poly(vinyl cinnamate) (PVCN) film with a thickness of 500 nm as the insulating layer was formed on the top of the gate electrode by spin-coating the polymer solution in the mixture solvent of monochlorobenzene and toluene. The PVCN film was photochemically crosslinked by exposing the film to UV with the wavelength of 254 nm for 20 minutes. Another narrow line pattern of electrically conducting polymer working as not only source-drain electrodes but also active layer was formed on the top of the insulating layer in the perpendicular direction to the gate electrode by the same patterning method. The thickness and width of active layer was 100 nm and 100 μm, respectively.

We investigated the properties of the vapor polymerized PEDOT film such as the electrical, optical and morphological properties. Electrical

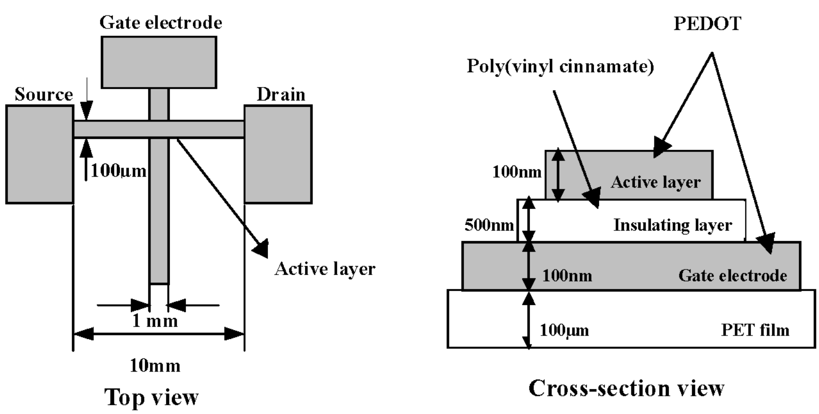

FIGURE 1 Structure of the All-polymer FET.

conductivity of the PEDOT thin film was determined as the surface resistivity and the existence of the free carrier tail absorption in near IR region. Surface morphology of the film was observed using an atomic force microscope (AFM). We also measured properties of the PEDOT pattern such as the electrical resistance of the patterned PEDOT line and the patterning resolution.

Electrical properties of the FET were investigated by observing the change of the relationship between source-drain current (I_{SD}) and voltage (V_{SD}) upon sweeping gate voltage (V_G) at room temperature. From the I_{SD}-V_{SD} and I_{SD}-V_G characteristics, we calculated the turn-off gate voltage, the trans-conductance and the on/off ratio of the FET. We also studied time dependence of the FET by measuring the change of the source-drain current upon applying pulsed gate voltage.

3. RESULTS AND DISCUSSION

We observed the surface resistivity and the transmittance of the PEDOT film decreased with increase of FTS content in the oxidant film, certainly because of more incorporation of PEDOT in the film. Surface resistivity and transmittance at 500 nm of PEDOT film obtained in this study was in the range of $10^2 \sim 10^4\ \Omega/\square$ and $50 \sim 95\%$, respectively. This indicates a highly conducting and fairly transparent PEDOT film can be obtained by the vapor polymerization used in this study. PEDOT film prepared with FTS weight ratio to PVA of 8:1 showed the surface resistivity of $3.6 \times 10^2\ \Omega/\square$ with the transmittance of 60%. We also confirmed high conductivity of PEDOT film from the absorption spectrum as shown in Figure 2, where a strong free carrier tail was observed in near IR region. Surface morphology of PEDOT

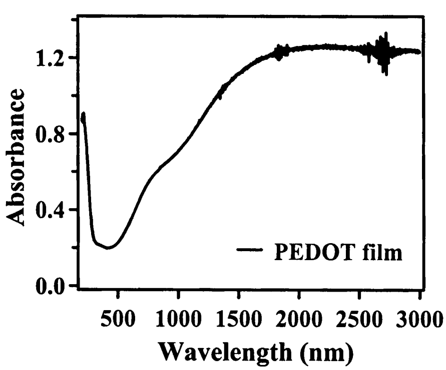

FIGURE 2 UV-VIS-NIR spectrum of PEDOT film prepared by vapor polymerization.

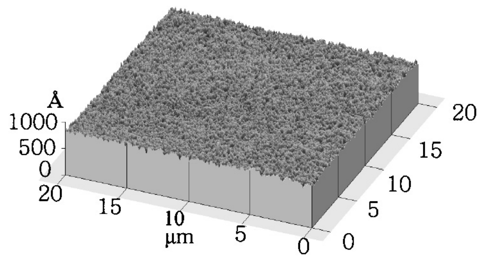

FIGURE 3 AFM image of the surface of PEDOT film prepared by vapor polymerization.

film was extremely smooth as shown in Figure 3, where the average surface roughness was about 10 nm. We, therefore, considered the PEDOT film prepared by the vapor polymerization could be used as the electrodes and the active layer of OFET.

We figured out the micro-pattern of the electrically conducting polymer with good resolution could be obtained by the simple photolithographic method as shown in Figure 4, where the dark area represents micro-patterned PEDOT line. We have successfully obtained patterns with the line width as low as 30 µm. The electrical resistance of the patterned line with the width of 100 µm and the length of 1 cm was of $4.2 \times 10^5\,\Omega$. Therefore, we suggest the photolithographic patterning technique can be used to form the electrodes and the active layer of OFET.

Figure 5(a) displays the relationship between I_{SD} and V_{SD} upon sweeping positive gate voltage from 0 to +35 V, where V_{SD} was scanned from 0 to +20 V. We found that I_{SD} decreased with increase of the positive gate voltage. This indicates the p-type FET works in a depletion mode. Holes are the major charge carriers in the p-type PEDOT active layer, thus

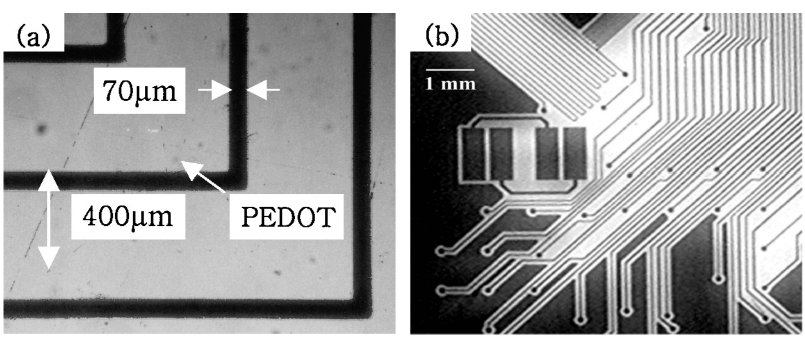

FIGURE 4 Microphotograph of the electrically conducting PEDOT micro-patterns.

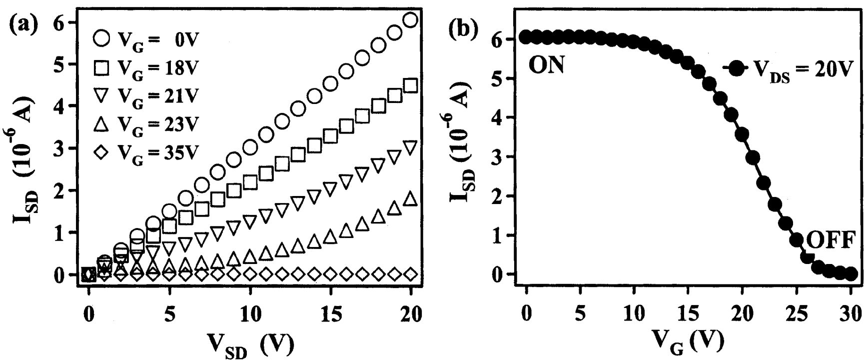

FIGURE 5 Electrical characteristics of All-polymer FET.

we believe the holes in the active layer depleted upon applying positive gate voltage.

Figure 5(b) shows the change of I_{SD} with the gate voltage from 0 to +30 V at a fixed V_{SD} of +20V. I_{SD} started decreasing at the gate voltage of +10 V and reached the minimum value at the turn-off gate voltage of about +30 V. On/off ratio (I_{on}/I_{off}) at V_{SD} of 20 V, defined as the current ratio of $I_{on,max}$ to $I_{off,min}$, was about 10^4order. The trans-conductance (g_m) of the FET, defined as the slope of the plot of I_{SD} versus V_G, was about $-1.2\,\mu A/V$ at V_{SD} of 20 V.

We also studied time dependence of FET as shown in Figure 6, where time-dependent I_{SD} was measured upon applying pulsed gate voltage of +40 V at a fixed V_{SD} of +20 V. As shown in Figure 6, the response time of the transistor was much slower than those of the inorganic conventional FETs. The slow response of the FET is possibly due to the ionic inter-

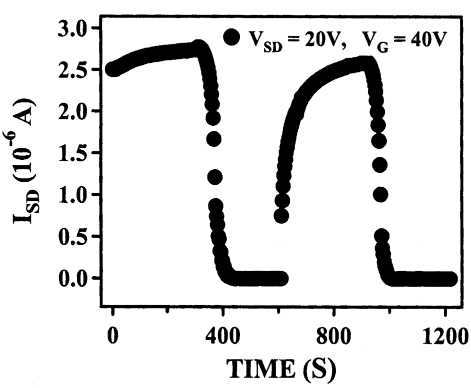

FIGURE 6 Time-dependent source-drain current.

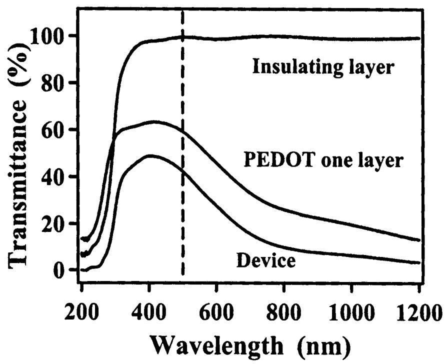

FIGURE 7 Transmission spectra of the All-polymer FET.

actions between PEDOT and dopant or various other ions in the active layer.

We consider All-polymer FET fabricated in this study may have significant advantages. Since the active layer is a part of the source-drain electrodes, the carrier injection is possibly easier in our device than in other devices with the heterojunction between the active layer and source-drain electrodes. We also believe the FET has good interface adhesion and electrical contact since all components of the device are polymeric materials. Figure 7 shows the absorption spectrum of the FET, exhibiting 50% transmittance at 500 nm. We, therefore, suggest the All-polymer FET fabricated in this study may be considered as a promising drive system of various devices requiring large area and mechanical flexibility.

4. CONCLUSION

We successfully fabricated the p-type All-polymer FET based on the simple photolithographic micro-patterning of electrically conducting PEDOT. Since all components of the FET such as substrate, electrodes, active layer and insulating layer were polymeric materials, the device showed fairly high transmittance and flexibility. We found that the p-type FET works in a depletion mode upon applying positive gate voltage. The turn-off gate voltage, the trans-conductance and the on/off ratio were about $+30\,V$, $-1.2\,\mu A/V$ and 10^4, respectively.

Since all components of the FET could be formed by spin-coating at room temperature and since the active layer was simultaneously formed in the middle of the source-drain electrodes, the fabrication required a simple and low-cost process. We, therefore, believe the All-polymer FET is applicable as a drive system of flexible and transparent electronic systems.

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