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Fabrication and Evaluation of Poly(3-hexylthiophene) Field-Effect Transistor With V_2O_5 Layer

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Organic field-effect transistors (OFETs) were fabricated using poly(3-hexyl thiophene) (P3HT), and the effects of inserted Lewis-acid thin layers on electrical properties were investigated. The OFETs have active layers of P3HT and vanadium pentoxide (V_2O_5) as a Lewis-acid layer. Larger drain currents were observed for the OFET with the V_2O_5 layer than that without the layer. The calculated field-effect mobility of the fabricated OFET was $1.4 \times 10^{-2}\ cm^2/(Vs)$, where as that of the OFET without the V_2O_5 layer was $6.2 \times 10^{-3}\ cm^2/(Vs)$. It was thought that charge transfer (CT) complex which was formed at the interface between P3HT and V_2O_5 layer was dissociated by gate voltage, and the generated holes seem to contribute to drain current and the apparent high mobility.

Keywords Charge transfer complex; Lewis-acid; organic field-effect transistor; vanadium pentoxide

1. Introduction

Organic field-effect transistors (OFETs) have been attracting significant interest because of their various advantages such as flexibility; further, their fabrication processes are simple. OFETs have potential for applications to organic light-emitting diode (OLED) displays. Many studies on OFETs have been reported [1–3]. In recent years, the properties of OFETs have improved significantly due to the improvements in the device structure [4–8], materials [9–11], and fabrication techniques [12–14]. However, OFETs have many drawbacks. One of the major drawbacks of OFETs is that their mobility and conductivity are lower than those of inorganic thin film

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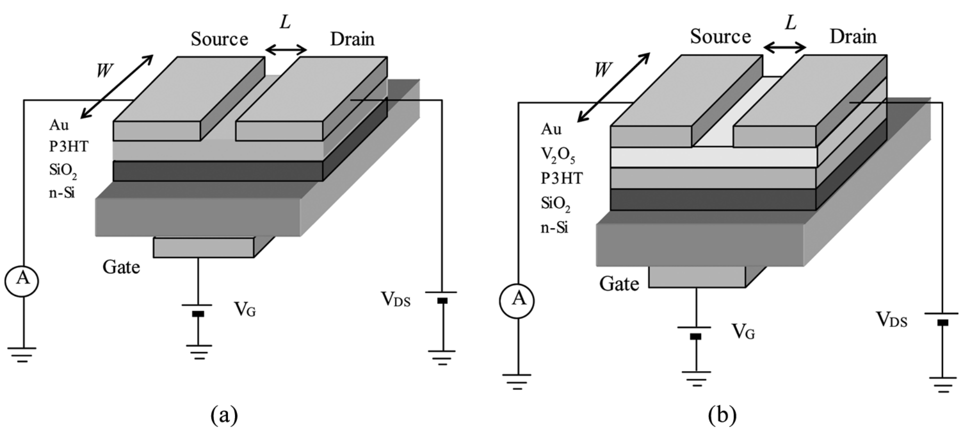
transistors. However, efforts are being made to improve these properties by using organic materials with high crystallinity, such as pentacene [15], or monocrystalline materials [16], for the active layer. The OFETs used in the driving circuit of high-brightness OLED displays have to supply a large current to the displays. Therefore, it is very important to develop OFETs with high mobility, which will also aid in reducing the electric power consumption of OLED displays and other devices.

In this study, OFETs using active layer of poly(3-hexylthiophene) (P3HT) with thin vanadium pentoxide (V_2O_5) layer are fabricated, and attempts are made to improve their mobility. It is well known that P3HT is excellent hole-transporting materials and can be used for the fabrication of OFETs [17]. The V_2O_5 layer is also known as a Lewis-acid layer, and it has been reported that the luminance efficiency of OLEDs is greatly improved by the insertion of a Lewis-acid layer in OLEDs [18–20]. In our previous papers, we have reported that the improvement of the field-effect mobility was observed by the insertion of V_2O_5 layer between the CuPc and SiO_2 layers [21,22]. It was estimated that the charge-transfer (CT) complex of CuPc and V_2O_5 contributed to the phenomena. In this study, the OFET property is investigated for the device with V_2O_5 layer between the top-contact electrode and P3HT layers. The contribution of the V_2O_5 layer thickness to the improvement in OFETs is also investigated in this study.

2. Experimental

The device structures we prepared in this work are shown in Figure 1(a) and (b). OFETs were fabricated on heavily doped *n*-type Si wafers, which were oxidized to form a 100-nm-thick SiO_2 layer on the surface. Device 1 has a structure of Al gate electrode/n-type Si substrate/SiO_2/ P3HT/Au source (S) and drain (D) electrodes. A ca. 10-nm-thick P3HT layer was fabricated on the SiO_2 surface by spin-coating method, and gold was deposited on the P3HT layer to form source and drain electrodes. *P3HT film was stably fabricated in our study, and the thickness of P3HT layer*



(a) (b)

Figure 1. Schematic diagrams showing structure of fabricated organic field-effect transistors: (a) with ca. 10-nm-thick P3HT (device 1), and (b) with ca. 10-nm-thick P3HT and 1-nm-thick V_2O_5 layers (device 2). OFETs with only a 20-nm-thick V_2O_5 layer as an active layer was also fabricated. The OFET with only a V_2O_5 layer did not exhibit the typical FET characteristics.

was measured by contact type surface roughness profiler (Veeco, Dektak 3). OFETs with a 1-nm-thick V_2O_5 layer was also fabricated as a device 2 which has an Al gate electrode/n-type Si substrate/SiO_2/P3HT/V_2O_5/Au source and drain electrodes structure. A V_2O_5 layer was successively deposited on P3HT layer by vacuum evaporation. For comparison, OFETs with only a V_2O_5 layer as an active layer was also fabricated. Device performance characteristics were investigated using a semiconductor parameter analyzer (Hewlett-Packard, 4145B) in nitrogen atmosphere at room temperature.

3. Results and Discussion

Figure 2 shows a drain current (I_{DS}) vs drain-source voltage (V_{DS}) plot for an OFET without a V_2O_5 layer (device 1) operated at various negative gate voltages (V_Gs). When a negative V_G was applied, typical I_{DS}-V_{DS} curves were observed in the FET. I_{DS} increased linearly with V_{DS} before gradually leveling off to approach

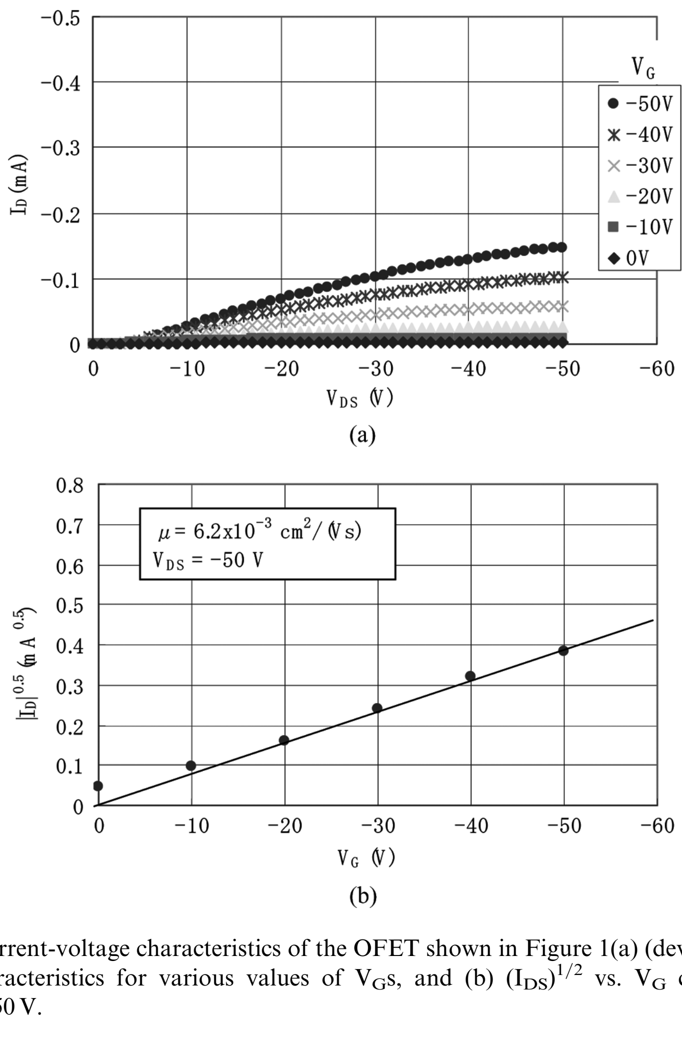


Figure 2. Current-voltage characteristics of the OFET shown in Figure 1(a) (device 1): (a) I_{DS} vs. V_{DS} characteristics for various values of V_Gs, and (b) $(I_{DS})^{1/2}$ vs. V_G characteristics for $V_{DS} = -50$ V.

current saturation. Current saturation was observed in Figure 2(a). It is known that the field-effect mobility of an OFET can be estimated using Eq. (1) as in conventional metal-oxide-semiconductor FETs (MOSFETs):

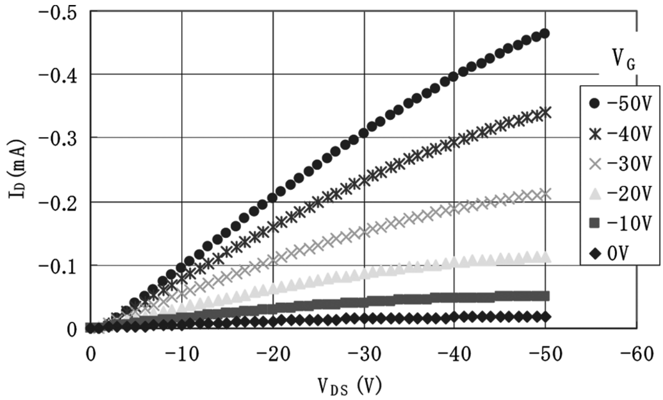
$$\mu = \frac{2LI_{DS}}{WC_i(V_G - V_t)^2}, \tag{1}$$

where μ is the channel mobility, C_i is the capacitance of the gate oxide layer, W is the channel width, L is the channel length, and V_t is the threshold voltage. These parameters were $C_i = 1.6 \times 10^{-7}\,\mathrm{F/cm^2}$, $W = 0.15\,\mathrm{cm}$ and $L = 15\,\mu\mathrm{m}$ in this OFET. A $(I_{DS})^{1/2}$ vs V_G plot is shown in Figure 2(b). The field-effect mobility of the OFETs, calculated from the slope of this curve, was approximately $6.2 \times 10^{-3}\,\mathrm{cm^2/(Vs)}$.

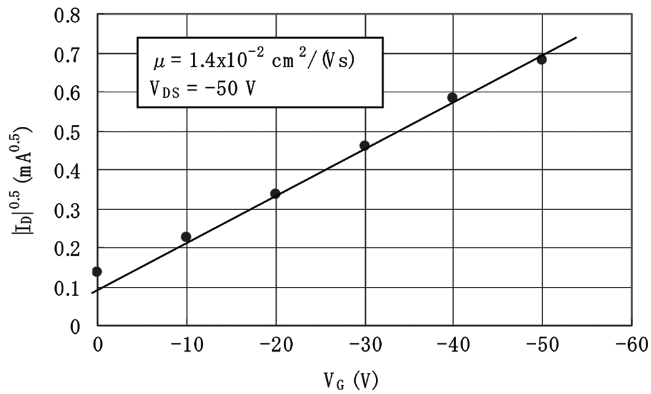
The I_{DS}-V_{DS} plot for the OFET with a V_2O_5 layer (device 2) operated at various negative gate bias voltages is shown in Figure 3. In this OFET, a larger drain current was observed than device 1, and I_{DS} increased linearly with V_{DS}, although current saturation was observed indistinctly in Figure 3(a). The calculated apparent mobility of this FET from Eq. (1) was $1.4 \times 10^{-2}\,\mathrm{cm^2/(Vs)}$, when the parameters in Eq. (1) were $C_i = 1.6 \times 10^{-7}\,\mathrm{F/cm^2}$, $W = 0.15\,\mathrm{cm}$ and $L = 15\,\mu\mathrm{m}$. This calculated apparent mobility was about twofold that of the OFET without a V_2O_5 layer (device 1). *The leakage gate currents (I_Gs) due to various gate-source voltages (V_Gs) of each device are almost the same as shown in Figure* 4, *therefore the differences between Figures* 2 *and* 3 *are not caused by the leakage current.*

We have proposed a operating mechanism of OFET with a V_2O_5 layer in the previous papers [21,22] that the charge transfer (CT) complex formed at the interface between the organic layer and V_2O_5 layers because of the interaction between the molecules. The CT complex dissociates due to the electric field of the gate voltage, and the generated holes are injected to the organic layer and contribute to the improvement of I_{DS}. Figures 5(a) and 5(b) show the estimated behavior of CT complexes at interface between P3HT and V_2O_5 layers in device 2. The CT complex formed at the interface between the P3HT and V_2O_5 layers has a positive polarity on the P3HT-layer side and a negative polarity on the V_2O_5-layer side. Therefore, negative V_G for device 2 induces CT complex dissociation as shown in Figure 5(b), and I_{DS} seems to be improved.

In this study, we investigated a thickness dependence of a V_2O_5 layers on I_{DS} in an OFET with a V_2O_5 layer. Figures 6(a) and 6(b) show I_{DS} vs V_{DS} plots for an OFET with 2-nm-thick and 5-nm-thick V_2O_5 layer operated at various negative V_Gs. In Figure 6(a), typical I_{DS}-V_{DS} curves were observed slightly when a negative V_G was applied, and a proportionality relationship between I_{DS} and V_{DS} was observed. A drain current in the off-state was increased with V_{DS} increasing. On the other hand, no typical I_{DS}-V_{DS} curves were observed in Figure 6(b). Proportionality relationships between I_{DS} and V_{DS} were observed clearly in an OFET with 5-nm-thick V_2O_5 layer. It was thought that an ohmic current might be dominant in an OFET with a V_2O_5 layer when a V_2O_5 layer was thick. *AFM images of 1-nm thick and 5-nm thick V_2O_5 layer surface were shown in Figures 7(a) and 7(b). It was confirmed that V_2O_5 layer was deposited inhomogeneously in 1-nm-thick sample, although a neat layer of V_2O_5 was fabricated in 5-nm-thick sample. Therefore*, the reason of this phenomenon was considered as follows. Figures 8(a) and 8(b) show



(a)



(b)

Figure 3. Current-voltage characteristics of the OFET shown in Figure 1(b) (device 2): (a) I_{DS} vs. V_{DS} characteristics for various values of V_Gs, and (b) $(I_{DS})^{1/2}$ vs. V_G characteristics for $V_{DS} = -50\,V$.

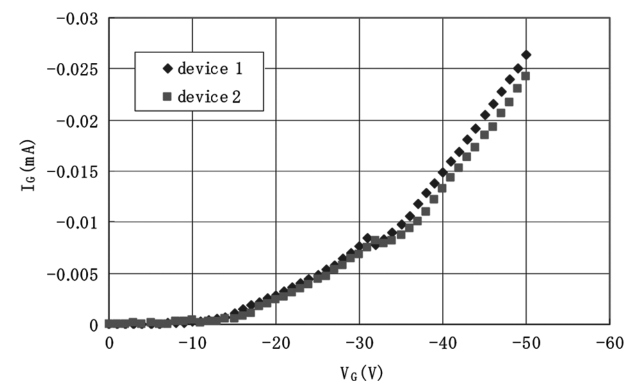
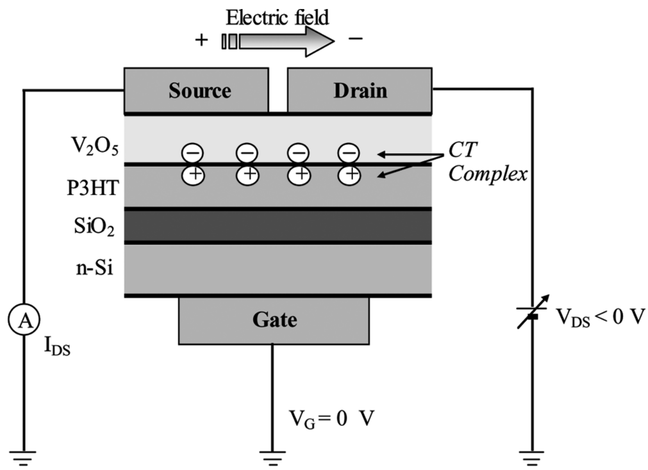
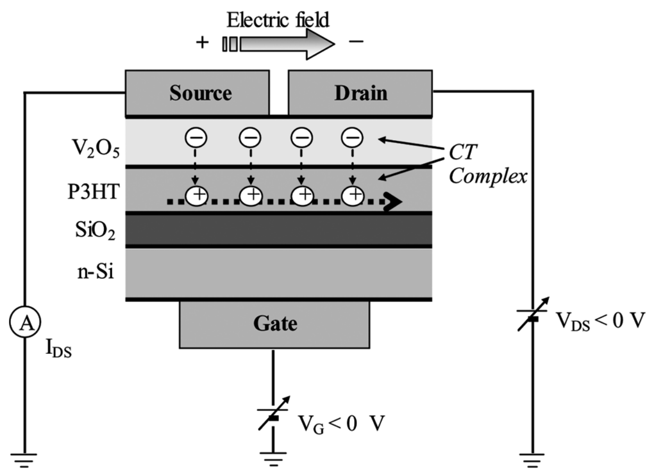


Figure 4. Leakage gate current (I_G) vs gate-source voltage (V_G) plots for an OFET without a V_2O_5 layer (device 1) and with a V_2O_5 layer (device 2).



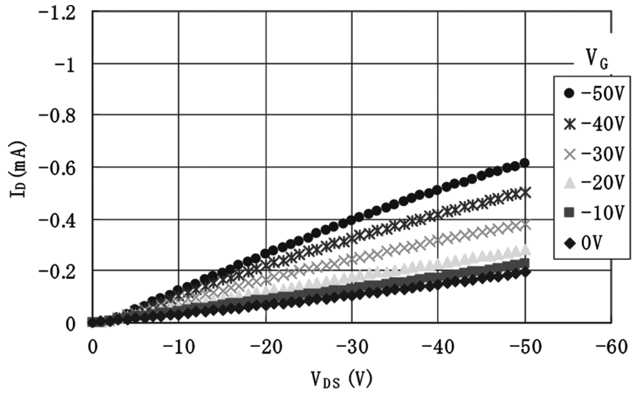
(a)



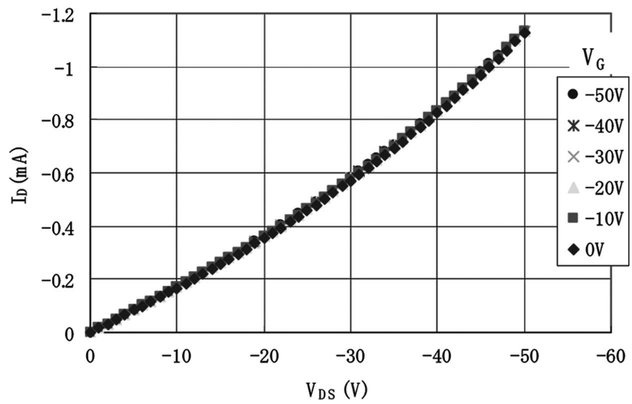
(b)

Figure 5. Schematics of active layers and behavior of CT complexes at interface between P3HT and V_2O_5 layers in device 2. The behavior of the CT complex of P3HT and V_2O_5: (a) for $V_G = 0\,V$, $V_{DS} < 0\,V$, and (b) $V_G < 0\,V$, $V_{DS} < 0\,V$ are shown in the figures.

estimated behaviors of CT complexes for thin and thick V_2O_5 layer in an OFET. It is known that CT complex is formed at the interface between organic layer and V_2O_5 layer. When a thickness of V_2O_5 layer was extremely small, V_2O_5 layer was fabricated inhomogeneously, and CT complex was formed partially as shown in Figure 8(a). However, CT complex was formed successively at the interface between P3HT and V_2O_5 layer as shown in Figure 8(b) when a thickness of V_2O_5 layer was thick enough to form a layer completely. It is thought that ohmic current was observed clearly because a carrier (hole) density in a P3HT-layer side was increased and a conductive channel was formed at the interface in spite of being off-state. Thus, it was found that optimization of V_2O_5 thickness was important for the OFET with a V_2O_5 layer.

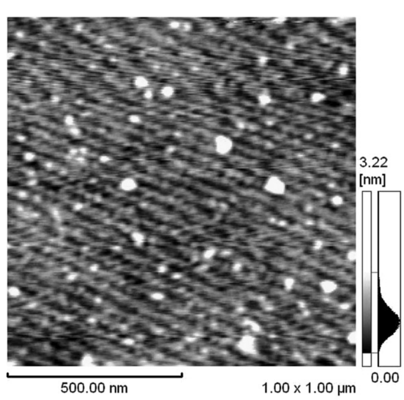


(a)

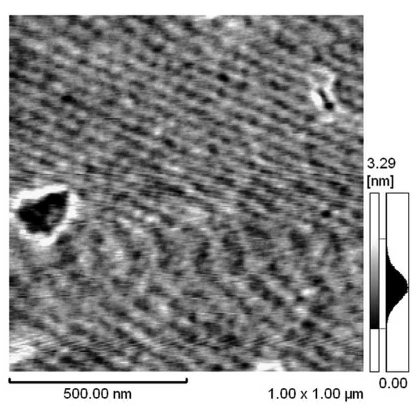


(b)

Figure 6. I_{DS} vs. V_{DS} characteristics for various values of V_Gs of the OFET: (a) with 2-nm-thick, and (b) 5-nm-thick V_2O_5 layers in device 2.



(a)



(b)

Figure 7. AFM images of V_2O_5 layer which was fabricated on glass substrate: (a) in case of 1-nm thick, and (b) in case of 5-nm thick.

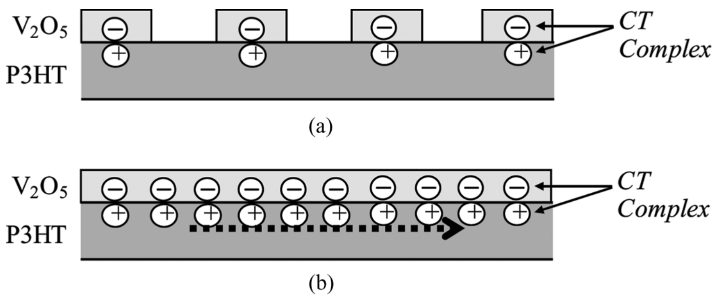


Figure 8. Schematics of detailed structure of active layers and behavior of CT complexes at interface between P3HT and V_2O_5 layers: (a) OFET with thin V_2O_5 layer, and (b) OFET with thick V_2O_5 layer.

4. Conclusions

Polymer type OFETs using P3HT with Lewis-acid layers were fabricated and their electrical properties was investigated. It was found that I_{DS} of the OFET with a V_2O_5 layer was 2 times higher than that of the OFET without a V_2O_5 layer, and the field-effect mobility of these OFETs was calculated to be $1.4 \times 10^{-2}\,cm^2/(Vs)$. It was estimated that the CT complex between P3HT and V_2O_5 contributed to the improvement of a drain current or a field effect mobility. It was also found that a property of OFET with a V_2O_5 layer depended on a thickness of V_2O_5 layer, and drain current would be improved in the OFET when a thickness of V_2O_5 layer was adequate.

The possibility of the performance improvement in a polymer-type OFET by the insertion of V_2O_5 layer was shown for the first time in this paper. Therefore, the results in this paper seem to be very useful for development of high performance OFET.

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