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Impedance Spectroscopy of Metal-Insulator-Polymer Semiconductor Diodes

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1. Introduction

Recently, organic field-effect transistors (OFETs) have attracted increasing interest for their possible applications in flexible and low-cost electronics such as flat-panel displays, electronic papers, and the radio frequency identification tags. The field-effect mobility of OFETs has been improved significantly over the last few years and a mobility of 0.6 $cm^2\ V^{-1}\ s^{-1}$ has also been demonstrated in OFETs fabricated from polymer semiconductors [1]. Recent study has been directed to the improvement of device performances including electronic stability for the practical use of OFETs. However, most of physical mechanisms that occur in OFETs are still not well understood. Further understanding of electric behaviors of organic materials and devices is essential for improving the performances of OFETs. The electrical characterization using metal-insulator-semiconductor (MIS) structures is inherently useful to study the electric behaviors compared to that using FET structures because of their one-dimensional nature. It has been shown that capacitance measurements as a function of voltage and frequency in organic MIS diodes give information on doping density [2], charge relaxation [3], and charge trapping [4] in organic semiconductors. However, a few attentions have been given to applying impedance spectroscopy (IS) to organic MIS diodes [5,6]. The IS has been widely used for studying in charge relaxation and transport processes in various electric devices based on organic and inorganic semiconductors. The analysis of impedance properties enables us to determine the equivalent circuits of devices, from which we can distinguish individual contributions from different sources such as bulk and interface layers and can gain insight into the electronic behavior of the devices.

In this paper, we report the detailed investigation for frequency and voltage dependence of the impedance properties of polymer MIS diodes fabricated using a polyimide (PI) as the insulator and a thiophene copolymer of poly(2,5-bis(3-alkylthiophen-2-yl)thieno[3,2-b]thiophene) (pBTTT) as the semiconductor by impedance spectroscopy. The equivalent circuit of the polymer MIS diodes is determined from the analysis of the impedance properties.

2. Experiments

The MIS diodes were fabricated on glass substrates with an indium tin oxide (ITO) thin layer on the surface, as shown in Fig. 1. An insulator layer was prepared on the ITO surface by spin-coating a solution of PI (Nissan Chemical Industries, LTD). It was cured at 85 °C at 1 h and subsequently at 185 °C at 1 h in air. A layer of pBTTT was then prepared by drop casting onto the PI layer from a 0.05 wt% xylene solution. After preparation, the device was annealed under vacuum at 100 °C for 1 h. Finally, a gold layer was evaporated onto the pBTTT layer through a shadowmask.

IS measurements were performed using a Sorlartron 1260 impedance analyzer with a 1296 dielectric interface in the frequency range from 10 mHz to 10 MHz and for applied voltages in the range of ±5 V under vacuum at room temperature. The experimental data were analyzed in terms of the complex modulus M, which was defined as $j\omega$ times the complex impedance Z, and loss G/ω, which was obtained from the admittance $G+j\omega C$ ($=1/Z$) of MIS diodes.

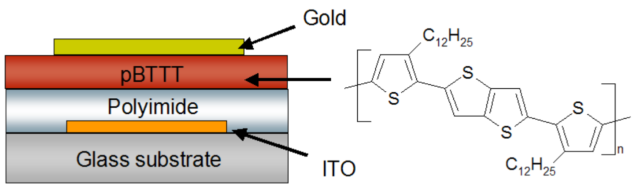

Fig. 1. Schematic cross section of the organic MIS diode and molecular structure of poly(2,5-bis(3-alkylthiophen-2-yl)thieno [3,2-b]thiophene) (pBTTT).

3. Results and Discussion

Figures 2(a) and 2(b) show the capacitance C and the loss G/ω of a fabricated MIS diode as a function of frequency for different voltages applied to the ITO electrode, respectively. In this voltage range, the device is partially depleted. In Fig. 2(a) the low-frequency capacitance decreases as the gate voltage is increased, indicating that a depletion region is formed at the PI/pBTTT interface and its width increases with gate voltage. It is seen in Fig. 2(b) that the loss spectrum reveals two dispersions below 1 kHz and above 100 kHz. The dispersion at higher frequencies is caused by the series resistance R_s associated with the electrodes. At high frequencies, the influence of R_s becomes predominant and the capacitance decreases remarkably. The low-frequency dispersions are mainly due to the resistance of pBTTT bulk (R_B). As is seen in Fig. 2(a), after the relaxation the measured capacitance becomes almost constant, at which the pBTTT layer works as a capacitance and the measured capacitance is equal to the series capacitances of PI (C_I) and pBTTT bulk layers (C_B).

Figure 3 shows the gate voltage dependence of the M plots of the MIS diode. The semicircle corresponds to the pBTTT layer, which can be represented by a parallel circuit consisting of R_B and C_B. It can be seen that as the gate voltage is increased the semicircle shifts to the positive direction and its diameter decreases. These results indicate that the effective thickness of the pBTTT layer decreases as the width of the depletion region at the PI/pBTTT interface increases, which is consistent with the results in Fig. 2. It is found that the semicircle is distorted as the gate voltage is increased. The distortion is likely caused by charge trapping in the distributed trap states at the semiconductor/insulator interface. From these results, it is found that the equivalent circuit of ITO/PI/pBTTT/Au MIS diodes can be represented by the serious circuit of the contact resistance R_S, two R-C parallel components of PI and pBTTT layers, and the depletion region C_D with interfacial trap states described by R-C series components, as shown in Fig. 4. The determined equivalent circuit yields a good fit to the experimental data, as shown in Figs. 2 and 3.

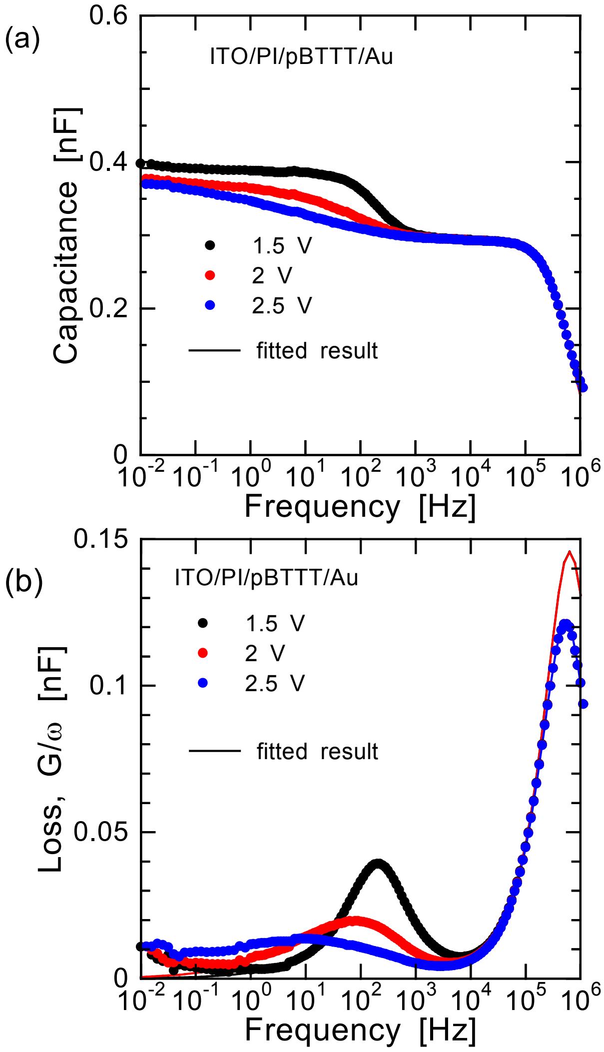

Fig. 2. Frequency dependence of (a) capacitance C and (b) loss G/ω of the ITO/PI/pBTTT/Au MIS diode at different gate voltages. Solid lines represent fitted results using the equivalent circuit in Fig. 4.

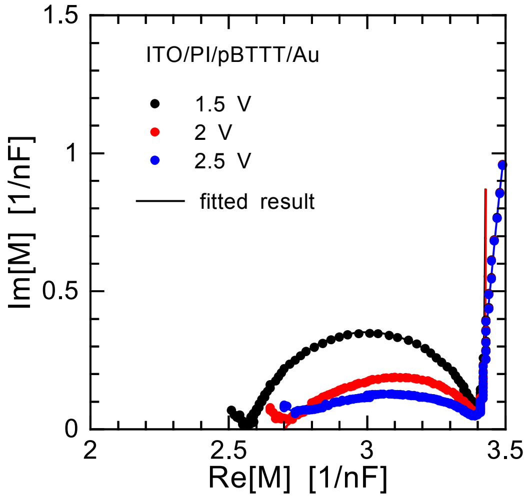

Fig. 3. Modulus plot of the ITO/PI/pBTTT/Au MIS diode at different gate voltages. Solid lines represent fitted results using the equivalent circuit in Fig. 4.

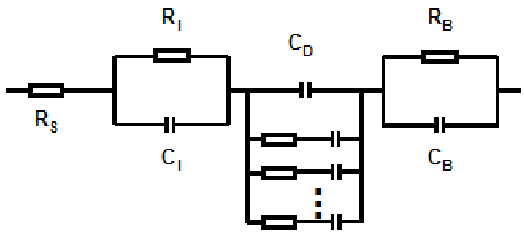

Fig. 4. Equivalent circuit of partially depleted ITO/PI/pBTTT/Au MIS diodes.

4. Conclusions

We have carried out impedance spectroscopy for polymer MIS diodes with pBTTT as a semiconductor layer. The MIS diode of ITO/PI/pBTTT/Au can be modeled by the equivalent circuit with interfacial trap states shown in Fig. 4.

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References

[1] I. McCulloch *et al.*, Nature Mater. **5**, 328 (2006).
[2] E.J. Meijer *et al.*, J. Appl. Phys. **93**, 4831 (2003).
[3] E.J. Meijer *et al.*, Appl. Phys. Lett. **78**, 3902 (2001).
[4] O. Marinov *et al.*, J. Vac. Sci. Technol. A **24**, 649 (2006).
[5] I. Torres, D.M. Taylor, and E. Itoh, Appl. Phys. Lett. **85**, 314 (2004).
[6] I. Torres and D.M. Taylor, J. Appl. Phy. **98**, 073710 (2005).