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Tuning of Threshold Voltage in Organic Field-effect Transistor by Dipole Monolayer

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1. Introduction

Recently, there has been a remarkable interest on organic field-effect transistors (OFETs) because of their unique advantages [1]. For practical use in electronics, it is necessary to precisely control all electrical properties. In addition to charge carrier mobility, the threshold voltage (V_{th}) is also an important parameter that needs to be tuned to achieve controllable OFET devices. It has been found that the threshold voltage is affected by bias stress [2], exposure to light [3] and can be shifted by using a ferroelectric gate insulator [4], ferroelectric interlayer between organic active layer and gate insulator [5] and self-assembled monolayers (SAMs) [6]. However, only recently it is possible to engineer surface dipoles at gate dielectric interface to manipulate the carrier density in channel and control the effective threshold voltage [7].

On the other hand, it is quite well-known that a variety of interface phenomena are very important in nano-science and modern physics because the surface is facing different environment compared with its bulk counterparts, and therefore presents many interesting properties. The Langmuir monolayer at air-water interface, as an ideal two dimensional system, is one of the most famous models to study interface phenomena, especially interfacial electronic property. Recently, we found that adding divalent cations into water subphase can increase dipole moment in normal of the amphiphilic molecules. Hence the effective amplitude of dipole moment can be regulated by adjusting the concentration of added divalent ions [8]. Therefore, it can be a useful technique to control threshold voltage by tuning the built-in electric field of a dipole monolayer.

In this study, an aligned dipole monolayer is introduced into OFET structure as an interlayer between pentacene and gate insulator (SiO_2) using the Langmuir-Blodgett (LB) technique. We then study the relationship between the dipole moment and threshold voltage shift experimentally and theoretically. A good agreement with experimental results and calculated data suggests us the capability of regulation of the threshold voltage of OFET.

2. Experiment

For the OFET structure, we fabricated a top-contact structure with dipole monolayer between organic active layer of pentacene and gate insulator of SiO_2. Highly doped Si wafers with 100 nm thermally grown silicon dioxide (SiO_2) insulating layer was used as substrates. Langmuir film of the dipole layer of dipalmitoylphosphatidylcholine (DPPC) was prepared on an aquatic subphase in a manner as in ref. [8]. Using the Langmuir-Blodgett (LB) technique, the Langmuir film was transferred to the clean substrate at a surface pressure of 20 mN/m at room temperature. After that, pentacene (from Tokyo Kasei Kogyou Co. Japan, without further purification) film was evaporated onto the deposited DPPC layer in a high vacuum around 2×10^{-4} Pa. The layer thickness was regulated using a quartz crystal microbalance (QCM) to 100 nm with a deposition speed of 0.5 Å/s. The source and drain electrodes with a thickness of 50 nm were formed by thermal deposition of Au onto the pentacene layer at a pressure of about 5×10^{-4} Pa. The channel length and width were 100 μm and 3 mm, respectively. At the same time a reference sample without dipole monolayer was also prepared. The OFET transfer characteristics were investigated by employing steady-state I-V measurement with a source meter (Keithley, type-2400). All of the measurements were carried out in ambient atmosphere.

3. Results and discussion

Figure 1 shows a typical transfer characteristics of the OFET with and without the dipole monolayer. It is easy to read that the drain-source current of reference sample is over two magnitude higher than that with the dipole monolayer at the same gate voltage. In addition, there is a large negative shift of threshold voltage from +4 V for reference sample to -18 V as shown in Fig. 1. It is instructive to note that this signicant shift is independent on applied voltage. For comparision, we made a simple calculation about threshold voltage shift, assuming that only the deposited dipole monolayer contibuted to the threshold voltage shift, that is, the origin of threshold voltage shift was due to built-in electric field (E_{bi}) induced by the deposited dipole interlayer. The electric field is counteracted by the additional applied gate-source voltage. Therefore, we obtain the following equations:

$$\Delta V_{th} = -E_{bi} t_{ox} \quad (1)$$

$$E_{bi} = \frac{V_m}{t_D} \quad (2)$$

$$V_m = \frac{\mu_\perp}{\varepsilon_0 A} \quad (3)$$

where ΔV_{th} is the additional applied gate-source voltage, namely threshold voltage shift, t_{ox} is the thickness of gate insulator (100 nm), V_m is the electrical potential difference access the dipole layer (its thickness: t_D) due to presence of the dipole monolayer, $\mu_\perp$ is dipole moment in normal, ε_0 is vacuum permittivity and A is molecular area (53 Å^2 in our case). The last equation is well-known Helmholtz equation giving the relation of dipole moment in normal and surface potential. Therefore, we obtain the relation between dipole moment and threshold voltage shift as follows

$$\Delta V_{th} = \frac{-t_{ox}}{\varepsilon_0 A t_D}\mu_\perp. \quad (4)$$

Substituting the above values, we got the threshold voltage shift of 20.7 V, which was in accordance with our experimental results (22 V).

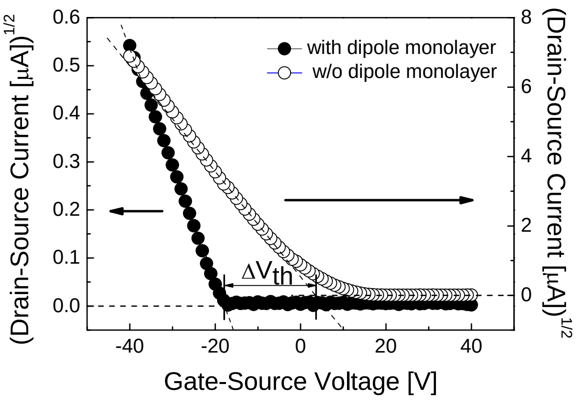

Fig. 1 Transfer characteristics of pentacene FET with (black dots) and without (white dots) a dipole monolayer interlayer between organic active layer pentacene and silicon oxide. The threshold voltage is evaluated from the saturation region.

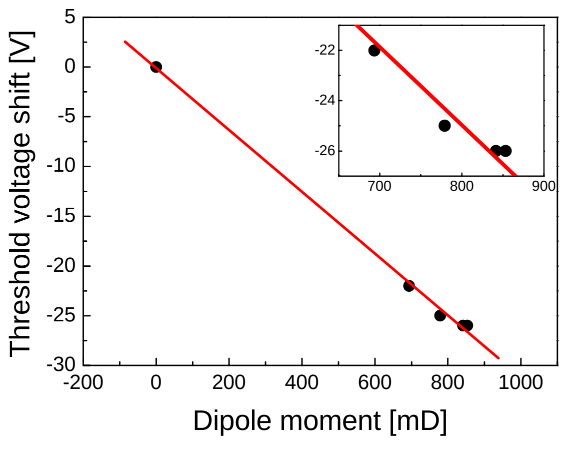

Fig. 2 Relation of threshold voltage shift and dipole moment of the deposited monolayer. Black dots are experimental data and the line is the linear fitting.

To verify and understand more about the relationship between threshold voltage shift and dipole moment, we plotted the experimental results of threshold voltage shift with respect to dipole moment of the deposited dipole layer, as shown in Fig. 2. Results shows that while dipole moment increased, the larger threshold voltage shift was induced. By fitting the points linearly, we obtain a slope of 0.0315 F^{-1}m^{-1}. Meanwhile, by calculating the slope with eq. (4), we obtained a slope of 0.0296 F^{-1}m^{-1}, which corresponds with the above experimental slope in the region of experimental error. This indicates it is possible to control threshold voltage by tuning the dipole moment of deposited dipole monolayer, which sheds a promising technique to make engineered organic device.

4. Conclusions

In order to understand the relationship between threshold voltage and internal electric field in OFET, we studied pentacene FET with a dipole monolayer between pentacene and gate SiO_2 insulator. The transfer characteristics showed the threshold voltage shifted to a negative value in accordance with the amplitude of electropositive dipole moment of the interlayer. Simple analysis quantitatively accounted for the experimental results. That is, the derived equation gives a clear relationship between the dipole moment and threshold voltage shift. In a word, using an engineered dipole layer is an effective way to control the threshold voltage of OFET.

Acknowledgements

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