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Probing of channel formation in organic field effect transistors by optical second harmonic generation measurement

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1. INTRODUCTION

The discovery of high mobility organic materials has called our attention to the development of organic field effect transistors (OFETs) [1]. Much experimental and theoretical effort has been made to improve the FET performance. It has been revealed that the device performance of OFET is quite different from that of Si-FETs. Carriers injected from the source electrode dominates the operation [2,3], a driving voltage is rather high in comparison with the voltage corresponding to the energy gap between HOMO and LUMO and so on. We need to pay more attention to the dielectric nature of organic materials, because the establishment of thermodynamic equilibrium over the entire region of OFET is difficult. Analyzing OFET from the viewpoint of dielectric physics is instructive. We have analyzed the OFET as a Maxwell-Wagner (MW) effect element [4,5], and showed that carrier injection from the source electrode makes a significant contribution to the carrier transport and the space charge formation. In the present study, to further clarify the carrier injection into the FET, we employ the optical second harmonic generation (SHG) measurements [6,7]. For pentacene FETs, SHG is enhanced at the off state due to Laplace electric field formation, whereas it is diminished at the on state due to the presence of additional injected carriers [5,7]. This reflects the channel formation by injected carriers. On the other hand, for Copper-phthalocyanine (CuPc) FETs, SHG was never observed at the off- and on- states, indicating that the electric field around the source and drain electrodes are being relaxed without depending on the off- and on-states of the FETs. From these results, we concluded that hole carrier injection into penatcene is smooth, but it is not into CuPc, and that SHG is a potential way to probe the electric field at the injection electrodes.

2. EXPERIMENT

Samples were top-contact (TC) pentacene FET and TC and bottom contact (BC) CuPc FETs, they were prepared in a manner as in our previous study [5]. Pentacene and CuPc were deposited at a substrate temperature of 350 K by thermal evaporation at a pressure less than 10^{-4} Pa. The deposition rate was about 0.04 nm/s. The thickness of the deposited pentacene and CuPc films was 100 and 80 nm, respectively. The TC (BC) FET channel length L and width W were 50 μm and 1.5 mm (50 μm and 110 mm). The current-voltage I_{ds}-V_{ds} characteristics were measured using a source-meter (Keithley type-2400). The SHG measurement was employed in the same manner as that in our previous studies [6,7], where fundamental light was focused on the channel region of the OFET using a convex lens. The light source was an optical parametric oscillator (OPO:Continuum Surelite OPO) pumped by the third-harmonic light of a Q-switched Nd-YAG laser (Continuum:SureliteII-10). Wavelength was fixed at 1320 nm for pentacene and at 1120 nm for CuPc. All measurements were performed in a laboratory ambient atmosphere.

3. RESULTS AND DISCUSSION

Typical FET characteristics were obtained for our pentacene and CuPc FETs with the Au source and drain electrodes, and these results were well analyzed using MW effect element model [6,7]. This means that the space charge field is formed in the FET channel at the on state of the FET due to the carrier injection to the interface between pentacene (or CuPc) and gate insulator. The effective mobility of pentacene and CuPc FETs were around 1.30×10^{-2} cm^2/V s (at $V_{gs} = -100$V) and 1.20×10^{-4} (at $V_{gs} = -40$V) cm^2/V s, respectively. Figure 1 shows the response of the SHG from pentacene FET with applying voltages at a wavelength of 1320 nm. Applied voltage sequence is as follows; Region 1 (V_{ds} = 0 V, V_{gs} = 0 V) → Region 2 (V_{ds} = −90 V, V_{gs} = 0 V) → Region 3 (V_{ds} = −90 V, V_{gs} = −90 V) → Region 4 (V_{ds} = −90 V, V_{gs} = 0 V) → Region 5 (V_{ds} = 0 V, V_{gs} =

0 V), where V_s= 0 V. Regions 1 and 5 are the initial state, regions 2 and 4 correspond to the off-state, and region 3 corresponds to the on-state. The on-state current I_{ds} is about 6 μA whereas it is nearly zero at the off-state (not shown). SHG is enhanced under the non-zero source-drain voltage V_{ds} in region 2. Since the channel conductance is generally low at zero gate bias (off-state), SHG process is induced by the electric field (EFISHG) [8] applied to the insulating pentacene layer parallel to the channel. In region 3, the enhanced SHG signal drastically decreases with applying the gate voltage V_{gs}, and then the SHG intensity completely recovers after the gate voltage is turned off (region 4). Interestingly, this remarkable change coincides well with the FET characteristics. That is, decrease of the SHG intensity corresponds to the increase of the drain current I_{ds} due to the FET operation (on-state), which accompanies the carrier injection from the Au source electrode. The electric field is relaxed due to the carrier injection, in particular at the interface, and this is the possible process to diminish the SHG. Note that the SHG enhancement is distinctive around the electrodes because of the concentration of local electric field [9].

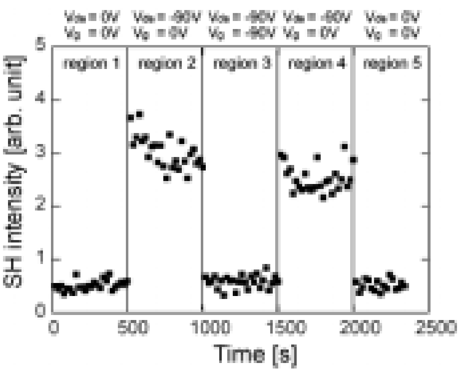

Fig.1 Response of the SHG from pentacene FET

Figures 2(a) and 2(b) show the response of the SHG from CuPc FETs and its drain current I_{ds} with applying bias voltages as follows: Regions 1,4,7 (Zero; V_{ds} = 0 V, V_{gs} = 0 V), Regions 2,5,8 (Off; V_{ds} = -100 V, V_{gs} = 0 V), and Regions 3,6,9 (On; V_{ds} = -100 V, V_{gs} = -100 V) of the BC and TC CuPc FET. The SHG measurements were carried out using a laser beam with a spot size of about 20 μm. As shown in Fig. 2, the SHG signals were not enhanced during the measurement, whereas the transient drain current was generated at on state (Fig. 2(b)). This result indicates that the electric field near the electrode-CuPc interface is being relaxed on both off- and on-states. This result illustrates us quite different picture of the electronic structure of the electrode–organic interface between CuPc and pentacene. In other words, the electric field at the electrode does not change so much by application of external electric field in case of CuPc FET, whereas it changes greatly for pentacene.

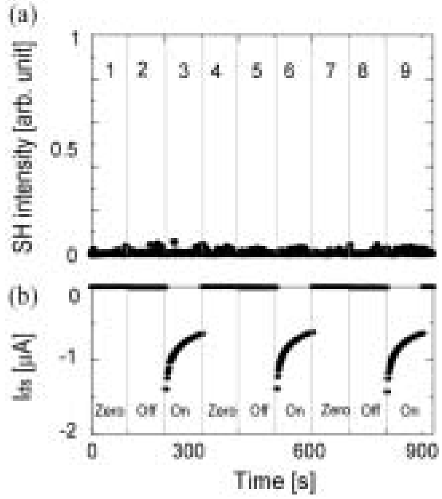

Fig.2 Response of (a) SHG with applied bias and (b) drain current I_{ds} for BC CuPc FET.

4. CONCLUSION

Carrier injection into the pentacene and CuPc FETs channel were investigated by the SHG measurements, on focusing of the electric field formed around the electrodes at the off- and on-states. This experiments revealed the difference in the off- and on-states of the electric field around the injection electrode.

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