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Analyzing Effect of Traps on Carrier Transport in Pentacene FETs with Polymer Gate Insulator by Pre-Biasing Method Coupled with Time-Resolved Microscopic Optical Second-Harmonic Generation Measurement

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Abstract

Carrier motion in pentacene organic field effect transistors (OFET) with polymer gate insulators, CYTOP and PMMA, is measured by using pre-bias time-resolved microscopic optical second-harmonic generation (TRM-SHG) measurement. The transient carrier mobility of the pentacene on the CYTOP is verified high in comparison with on the PMMA, suggesting that the carrier trap density of the OFET using the CYTOP is less than that using the PMMA. Results well account for the *I-V* behaviors of the OFETs with the CYTOP and PMMA gate insulators.

1. Introduction

Organic field effect transistor (OFET) is promising device for plastic electronics due to its flexibility and easy manufacturing. Considerable research has been conducted in the past decade to develop practical applications of OFETs. However, understanding of organic device physics is insufficient. In particular, insufficient understanding of the carrier trapping causes low reliability of the devices. For instance, carrier trap at an organic semiconductor interface is the origin of the hysteresis loop in the *I-V* characteristics and the gate voltage dependence of mobility [1, 2]. Hence, detailed evaluation of carrier traps is strongly required as well as a reduction of trap.

Recently, we developed the TRM-SHG technique for probing carrier motion in organic materials on the basis of the electric field induced SHG (EFISHG) under the device operation condition [3]. By using the TRM-SHG, we studied the trap-filling effect on transient carrier transport in pentacene FET. Applying gate voltage V_g as a trap-prefilling bias, we showed that the transient carrier transport was strongly dependent on trap-filling condition at pentacene and the gate-insulator interface, and effective carrier mobility increases with increase of the pre-filled trap density [4].

It is known that carrier behavior in the OFET strongly depends on the gate insulator, e.g., mobility enhancement with low-*k* dielectrics such as CYTOP [5-7]. In this study, we focused on the difference in carrier behavior between a pentacene FET with PMMA gate dielectric(hereafter we denote Sample A) and that with CYTOP gate dielectric (we denote Sample B) as a low-*k* insulator using TRM-SHG technique; the results well account for IV characteristic of these devices.

2. Experimental

Devices used here were top-contact FETs. A highly doped n^+-Si wafer with a 500 nm thick SiO_2 was used as a substrate, and SiO_2 surface is covered with a thin (40 nm) layer of PMMA (ε=4) or CYTOP (ε=2.1). Pentacene, as a p-type organic semiconductor material, is deposited on the substrate with a thickness of 100 nm using vacuum evaporation. Then after, the source and drain electrodes were deposited by thermal evaporation of Au. Channel length (L) of Sample A and Sample B 50 μm and 80 μm, respectively. Channel width (W) was 3 mm. All measurements were performed in laboratory ambient atmosphere.

For the prebias-SHG measurement, femtosecond Ti:sapphire laser is used, which can provide a high excitation power, so that we can measure SHG signal in high S/N ratio. Time-resolved experiment was performed by synchronizing the laser pulses and the voltage pulses applied to OFET. Figures 1 shows the setup for the TRM-SHG measurement and the timing chart of the time-resolved measurement.

The key of this measurement is applying the V_g prior to the V_s, that is, pre-bias. When V_g is applied (source and drain are grounded), holes are injected or extracted via top electrodes depending on the polarity of V_g. We call this operation "pre-bias". Using the pre-bias, we can control the carrier density in channel region of OFETs, thus the number of "effective" trap-sites can be intentionally decreased or increased. The detailed setup was described in Ref. [3]. A laser pulse (wavelength λ) was normally incident on the OFET channel through an objective lens, and EFI-SHG signal (wavelength λ/2) from pentacene was observed with a cooled CCD camera.

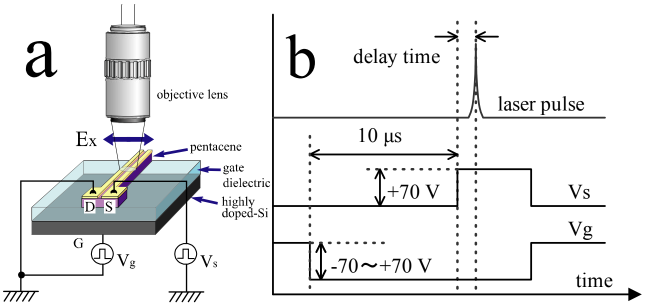

Fig. 1. (a) Schematic diagram of the pre-bias SHG technique. Using microscopic objectives, fundamental light is focused on device. (b) Timing chart of laser pulse irradiation and pulse V_s and V_g voltage.

3. Result and discussion

Fig 2 shows the saturated transfer curves of Sample A (red line) and Sample B (blue line) at V_{ds} = -100 V. The field effect mobility is 0.22 and 0.13 cm^2/Vs, and threshold voltage is -25 and -27 V, respectively.

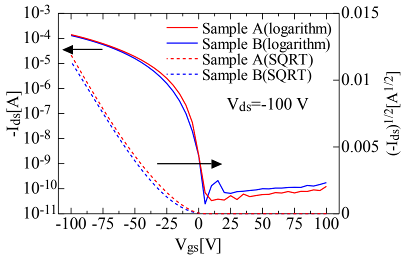

Fig. 2. Transfer characteristics of the pentacene OFETs measured at V_{ds}=-100 V in logarithmic (solid line) and square-root (dashed line). The blue lines represent Sample B (L = 80 μm, C_i=6.1×10^{-9} F/cm^2) and the red lines represent Sample A (L = 50 μm, C_i=6.6×10^{-9} F/cm^2)

Figures 3a and 3b show pre-bias voltage dependence of the square root of SHG intensity of Sample A and Sample B, respectively. For Sample A (Fig. 3a), sharp peak gradually decays and diffuses with the increase of the gate voltage V_g, and the SHG distribution spreads. This result, which coincides well with our previous work, indicates that the increase of V_g results in the decrease of empty trap sites, so that injected carrier can move smoothly [4].

In contrast, for Sample B (Fig. 3b), we could not observe the sharp peak. Besides the SHG intensity did not change and diffuse so much compared with the case of Sample A. It implies that the number of trap sites in Sample B is less than that in Sample A [8].

From figures 3a and 3b we can evaluate the mobility by using eq. (1) [9].

$$\mu = \frac{1}{2}\frac{\bar{x}^2}{V_s t} \qquad (1)$$

Here, t is the time we observed the SHG signal, x is the front position of SHG intensity, and V_s is the source voltage.

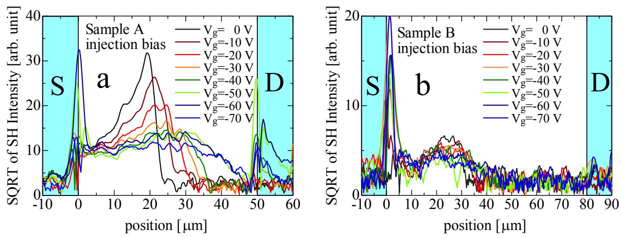

Fig. 3. SHG intensity profile measured by TRM-SHG experiment in the channel of (a) Sample A at 200 ns, (b) Sample B at 165 ns. The applied source voltage V_s is fixed at +70 V. The applied gate voltage V_g is from 0 V to -70 V as injection bias.

Fig. 4 shows the mobility evaluated by using eq. (1) at each pre-bias voltage. The results indicate that the mobility depends on applied pre-bias voltage. Accordingly, we divided the results into three regions, as shown in Fig. 4. In region 1, trapped holes are completely extracted due to large positive pre-bias voltage, so that the mobility is constant. In region 2 holes are injected from source and drain electrode during application of negative pre-bias voltage. Traps are partly and gradually filled by these injected holes. Accordingly, effective traps decrease with increase of negative pre-bias voltage. Finally, all traps are filled in region 3 due to high negative pre-bias voltage. Interestingly, we can observe the saturation of mobility in this region [4].

Sample B showed a higher mobility compared with Sample A in region 1 and 2. Furthermore, the voltage width of region 2 of Sample B is narrower than Sample A. These results indicate that the trap density in Sample B is smaller than Sample A; they well account for the I-V behaviors of these devices.

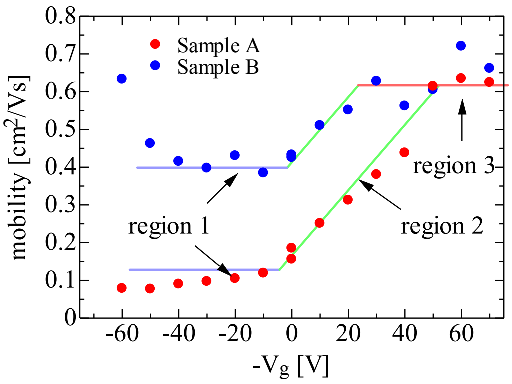

Fig. 4. The mobility measured by pre-bias SHG vs -V_g.

3. Conclusions

We introduced the trap-filling technique to OFET with low-k dielectric. Result indicates that the trap density in the OFET with CYTOP insulator is lower than that with PMMA insulator. The TRM-SHG measurement becomes a powerful tool to analyze the trap-dominated carrier transport in the OFET device.

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