

Surface Spectroscopy of Organic FETs for the Estimation of Effective Mass of Organic Semiconductors

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1. Introduction

An effective mass of a charge carrier in a semiconductor is a very important materials parameter that determines the highest possible device performance using the material. The effective masses of charge carriers in semiconductors have been determined by oscillatory behaviors of physical properties such as the Shubnikov-de Haas effect in strong magnetic fields at low temperatures, which is related with cyclotron resonances of the charge carriers. Since a long mean free time of the mobile carriers much longer than the cyclotron period is required for the observation of oscillatory behavior, it is very difficult to apply those techniques for amorphous/or polycrystalline materials such as ordinary organic semiconductors. Actually there have been no measurements of the effective masses in thin film organic semiconductors because of the low mobilities of their charge carriers. In order to establish a technique to characterize charge carriers in organic semiconductors, we are applying various surface spectroscopy techniques to organic thin film device structures [1,2]. In this paper, we focus on the attempt to estimate the effective mass of charge carriers in organics by the measurement of a plasma frequency of organic thin film transistors.

2. Experimental

Sample preparation and the measurement were performed in a ultrahigh vacuum system (UHV; base pressure 2×10^{-8} Pa) with two chambers, namely, a deposition chamber and an analysis chamber. In the deposition chamber, organic semiconductors were evaporated from Knudsen cells and deposited on a substrate with electrodes which forms a bottom-electrode type FET structure. The substrate was a highly doped Si wafer working as a gate (G) electrode with thermal oxide (thickness 200~700 nm) on the surface (Fig.1 (a)). On the oxide surface, Au/Cr source (S) and drain (D) electrodes were formed by a

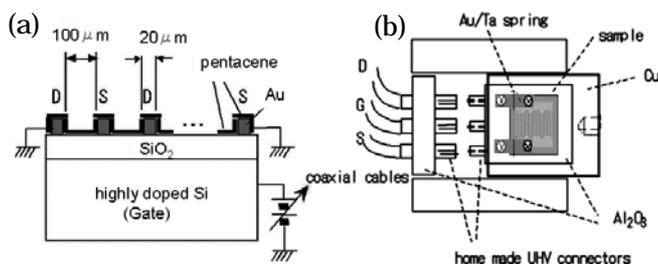


Fig. 1: (a) Sample structure and (b) experimental setup.

lift-off process. The substrate was mounted on a holder with electrical connections for the in-situ measurement of FET characteristics using coaxial cables (Fig.1 (b)). The substrate was heated at 150 °C for 4 hours in UHV prior to the deposition of organic semiconductor molecules. The deposition rate and the final thickness were controlled by quartz crystal microbalance. After the deposition, the sample was transferred to the analysis chamber. First, the device characteristics were measured in UHV and then the surface spectroscopy was performed. The analysis chamber is equipped with ultraviolet photoelectron spectroscopy (UPS) and electron energy loss spectroscopy (EELS). The electron energies were analyzed by an angle resolved electron analyzer. The primary electron beam for EELS was monochromatized. During the electron spectroscopic measurements, the S and D electrode were connected to the ground level. Macroscopic electric field from the gate electrode was shielded by the coaxial connectors and the conducting organic films.

3. Result and Discussion

Figure 2 shows the device characteristics of a pentacene FET with a thickness of 1.5 nm, which corresponds to 1 monolayer (ML). FET characteristics with a mobility of $\sim 0.004 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ is observed. EELS of this sample meas-

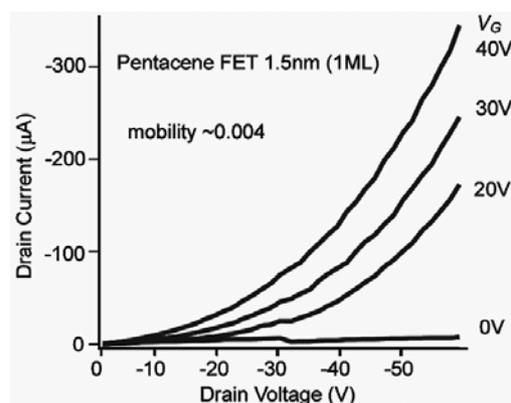


Fig. 2: FET characteristics of pentacene FET with the thickness of 1.5 nm

ured with applying various gate voltages (V_G) are shown in Fig.3. It is noticed that there are shoulders or additional peaks in the energy loss side and the loss energies of the peaks increased when V_G was increased. This is a behavior expected for the observation of plasma oscillation of charge carriers in a thin film FET. In order to measure the loss feature precisely, the data in Fig. 3 is processed by

deconvolution of the symmetric primary peak at $V_G = 0$, which corresponds to the apparatus function due to the energy spread of the primary electron beams and resolution of the electron analyzer (total FWHM = 180 meV). The result is shown in Fig. 4, in which the V_G -dependence of the new peaks is clearly observed.

The energy of plasma oscillation (volume plasmon) $\hbar\omega_p$ is written as

$$\hbar\omega_p = \hbar (ne^2 / \epsilon_0 m^*)^{1/2}, \quad (1)$$

where n, e, ϵ_0, m^* are the charge density, charge of the electron, electric permittivity of vacuum, and the effective mass of the charge carriers.

Since $n = c_{ox} V_G / d$, where c_{ox} and d are the oxide capacitance and the thickness of the semiconductor layer which contains mobile charges, it follows

$$\hbar\omega_p = \hbar (c_{ox} V_G e^2 / \epsilon_0 d m^*)^{1/2}. \quad (2)$$

The plasmon energies are calculated by using the parameters in the present experiment and indicated as arrows in Fig. 4. As the effective mass m^* , the maximum value $0.6 m_0$ in the direction-dependent m^* predicted from a band calculation is used[3] (Here m_0 is the an electron mass). The agreement between the observed peak energies and calculated ones is noticeable.

There are two types of plasmons, namely volume plasmons and surface/interface plasmons, and the latter has smaller energies than the former ones. The excitation probability and the intensity of those plasmons are dependent on the method of excitation and detection geometries. We expect that angle-resolved measurement of EELS and application of other excitation technique will reveal more precise information.

3. Conclusions

Surface spectroscopic techniques have been applied to characterize the charge carriers in organic FETs. A peak whose energy is dependent on the gate voltage has been observed in electron energy loss spectroscopy of a pentacene FET with monomolecular thickness. The peak energy is consistent with plasma oscillation of mobile carriers with an effective mass of $0.6 m_0$, which is in agreement with the reported estimation from a band calculation.

Acknowledgements

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References

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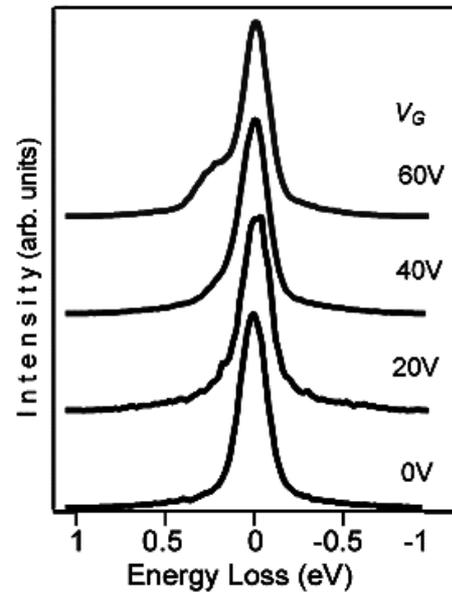


Fig.3: EELS of a pentacene FET (thickness = 1.5 nm) with applying various gate voltages. The energy of the primary electron beam was 15 eV.

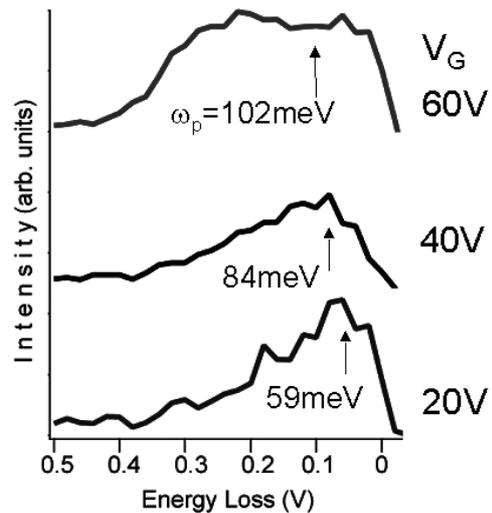


Fig.4: EELS feature without the contribution of primary electrons of a pentacene FET (thickness = 1.5 nm). The energy values with arrows are volume plasmon energies calculated with $m^* = 0.6 m_0$.