Extended Abstracts of the 2007 International Conference on Solid State Devices and Materials, Tsukuba, 2007, pp. 1078-1079

H-7-3

Analysis of charge accumulation in pentacene field effect transistor with ferroelectric gate insulator on the basis of Maxwell-Wagner model

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1. Introduction

Since the discovery of high mobility organic semiconductor materials, many experimental and theoretical efforts have been devoted to investigate organic field effect-transistors (OFETs). As a result, the performance of OFETs has been improved and many important aspects of OFETs' operation have been revealed. For example, it was found that carriers injected from the source electrode give a significant contribution to the operation of OFETs [1-3]. However, there are still many problems to be solved theoretically and experimentally. Among them are the control of threshold voltage of OFETs, and the analysis of the hysteresis behavior of the FET characteristics caused by carrier trapping, etc [4]. In order to solve these problems, we have to understand the mechanism of charge accumulation at the OFETs channel, and then to establish a method to control it. In the present study, we focus on the effect of the spontaneous polarization of gate insulator, which modulates the amount of accumulated charges at the OFETs' channel. Then, the characteristics of pentacene field effect transistor (FET) with a ferroelectric gate insulator is examined and analyzed on the basis of Maxwell-Wagner model for characterizing OFETs [4,5].

2. Experiment

The structure of pentacene FET with ferroelectric gate insulator is shown in Fig. 1. The ferroelectric gate insulator is copolymer of vinylidene fluoride and tetrafluoroethylene, i.e., P(VDF-TeFE). P(VDF-TeFE) films of 400 nm thickness were spin coated on the gate electrode using a 10 % solution of methylethylketone. The spontaneous polarization of our P(VDF-TeFE) film is estimated as P_0 = 22.4 mC/m^2 [6].

3. Results and Disccusion

Analyzing the FETs as a Maxwell-Wagner effect element [4-6], the charge per unit area given by

$$Q_s = \left(\frac{\tau_1}{\tau_2} - 1\right) C_g \left(V_{gs} - \frac{1}{2} V_{ds}\right) + P_0 \qquad (1)$$

is shown to be accumulated at the interface of pentacene/P(VDF-TeFE) in Fig. 1. Here, C_g is the capacitance of gate insulator, given by $C_g = \varepsilon_i \varepsilon_0 / d_i$ (ε_i and d_i are the relative dielectric constant and thickness of insulator, respectively. ε_0 is dielectric constant of vacuum). Eq. (1) indicates that the current I_{ds} flowing from source to drain is given by $I_{ds} = W Q_s \cdot \mu \cdot V_{ds} / L$ (W: channel width, μ: mobility) [5], but it is significantly affected by the change of the direction of spontaneous polarization P_0.

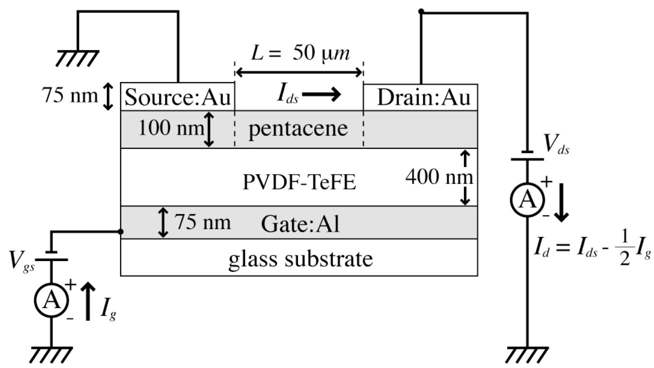

Fig. 1: The structure of pentacene FET with ferroelectric gate insulator

Firstly, in order to clarify the relationship between the spontaneous polarization of P(VDF-TeFE) and charges accumulated at the interface, the current I_g flowing across the FET is investigated under V_{ds} = 0V. The result is shown in Fig. 2. As the coercive field E_c of P(VDF-TeFE) is about 10^6 V/cm [6], it is expected that a current with one peak is observed due to the turn-over of the spontaneous polarization P_0, when a voltage applied to

P(VDF-TeFE) films, V_{PVDF}, reaches $E_c d_i = \pm 40$V. In Fig. 2, one peak was observed at V_{gs} = - 40 V because the turn over of P_0 changes the amount of accumulated charges at the pentacene/P(VDF-TeFE) interface given by eq. (1). When V_{gs} = - 40 V, pentacene is conductive because of hole injection from the source and drain electrodes, and the V_{gs} is mostly applied to the P(VDF-TeFE), i.e, $V_{gs} = V_{PVDF}$. Therefore $V_{gs} = E_c d_i$.

On the other hand, two peaks were observed in the I_g-V_{gs} characteristics in the region $V_{gs} > 0$. In our previous study, it was revealed that the first peak A is generated due to the exhaustion of accumulated holes at the interface in the direction to the source and drain electrodes [7]. Because in the same region, the capacitance decreases in C-V characteristics, i.e., charges release from pentacene film along the electric field in the FET. And the origin of the peak B at V_{gs} = 62 V is due to the ferroelectric polarization of P(VDF-TeFE). Here, the absolute value of voltage causing the turn over of P_0, V_c^+, in positive V_{gs} region is greater than a voltage V_c^- = - 39.8 V in negative V_{gs} region. The physical reasoning is that the pentacene functions as a conductor at $V_{gs} = V_c^-$ as mentioned above, whereas it functions as an insulator at $V_{gs} = V_c^+$ due to the exhaustion of holes accumulated at the interface. Taking into account these, it is expected $V_{PVDF} = C_1/(C_1+C_g)V_{gs}$. Therefore, the condition for the turn-over of spontaneous polarization P_0 is given by

$$\frac{C_1}{C_1 + C_g} V_{gs} = E_c d_i, \qquad (2)$$

where C_1 is the capacitance of pentacene per unit area, obtained as $C_1 = \varepsilon_{penta}\varepsilon_0/d_{penta}$ (ε_{penta}; relative dielectric constant, d_{penta}; thickness of pentacene). That is, $|V_c^-/V_c^+| = C_1/(C_1+C_g)$ is satisfied. For ε_{penta} = 3 [8], ε_i = 7.2, d_{pemta} = 100 nm and d_i = 400 nm, $|V_c^-/V_c^+| = C_1/(C_1+C_g)$ = 0.63. This is nearly the same value as the experimental one of $|V_c^-/V_c^+|$ = 0.65 (V_c^- = -39.8 V, V_c^+ = 62 V). Further, it is instructive to discuss absolute values of displacement charges caused by turn-over of spontaneous polarization. The displacement of charges with turn-over of P_0 at V_c^- is given by $Q_{P0}^- = 2P_0$ because the second term of eq. (1) changes from $-P_0$ to $+P_0$. However, it is not valid when we discuss displacement of charges Q_{P0}^+ at V_c^+ because there is no accumulated charge in pentacene films. On gate electrode, charge Q'_s given by

$$Q_s' = \frac{C_1}{C_1 + C_g} P_0 \qquad (3)$$

is induced due to the spontaneous polarization P_0 when pentacene functions as an insulator. Therefore, the density of displacement charges Q_d^+ with the turn-over of P_0 is given by $Q_d^+ = C_1/(C_1+C_g) \cdot 2P_0$. From these relationships described above, $|Q_d^+/Q_d^-|$ is also obtained as $|Q_d^+/Q_d^-| = C_1/(C_1+C_g)$ = 0.63. However, the experimental value is $|Q_d^+/Q_d^-|$ = 0.21, where Q_d^+ and Q_d^- is derived by integrating current peaks B and C in Fig. 2. The reason of deviation of the experimental value from the theoretical value is as follows: when peak A around V_{gs} = 35.3 V is observed, the movement of holes is induced by turn-over of most part of spontaneous polarization P_0. As a result, only a part of P_0 contributes to current peak B at V_{gs} = 62 V, and displacement charge Q_d^+ with turn-over of P_0 and $|Q_d^+/Q_d^-|$ are much smaller value than expected ones. Further experiments and analysis on the FET characteristics will be also presented based on a Maxwell-Wagner model.

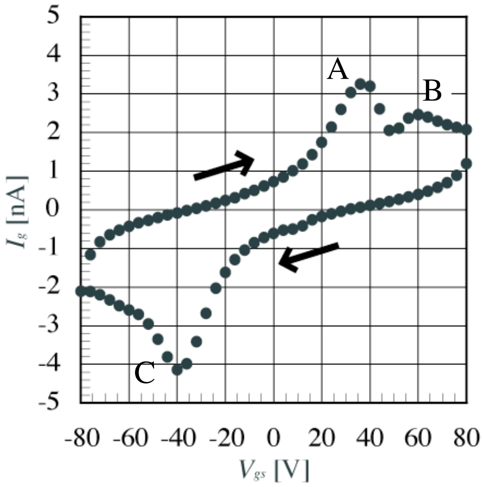

Fig. 2: I_g - V_{gs} characteristics of pentacene FET with ferroelectric gate insulator at V_{ds} = 0 V

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