Interface Charging Propagation Model for Carrier Migration in OFET

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1. Introduction

Semiconductor devices using organic materials, such as thin film transistors and light emitting diodes have attracted a lot of research interests. With the development of organic materials with high mobilities, recent research of the organic field effect transistors (OFETs) has been concentrated on the applied research mostly to increase the carrier mobility. However, the device physics of OFET is not yet clear in comparison with that of inorganic FET structures and transient phenomenon of carrier propagation is without deep understanding.

In this contribution we report on the propagation of injected carriers. Charge migration is evaluated by the transmission line model and discussed for three-electrode systems, *i.e.*, OFETs. On the basis of this analysis we find different carrier transport mechanism: (i) the drift in electric field of the two-electrode system or (ii) charge accumulation propagation on the pentacene - gate insulator interface of the three-electrode structure. In the end we show mobility evaluation from the capacitance measurement, which is in good agreement with value obtained by the standard current-voltage (I-V) experiment.

2. Experiment

Samples used in experiments were top-contact pentacene OFETs. Heavily-doped Si wafers with a 100 nm thick thermally prepared silicon dioxide (SiO₂) insulating layer were used as the base substrates. During the deposition of pentacene (100 nm), the pressure was kept at less than 10^{-4} Pa and the deposition rate was fixed at 0.5 Å/s. Afterwards, gold electrodes (Source and Drain electrodes) of a thickness 50 nm were deposited on the pentacene surface. The designed channel length (L) and width (W) were 100 µm and 3 mm, respectively.

The created structures were investigated by standard I-V analysis using Keithley 2400 SourceMeter, as well as frequency dependence of the capacitance (C-f) using Solar-tron 1260 impedance/gain-phase analyzer. C-f was applied to investigate the carrier transport and injection phenomena; the Source and Drain electrodes were short-circuited, and the potential was applied in the vertical direction to investigate carrier injection and spreading.

The I-V characteristics of the OFET sample was first verified and confirmed to show typical behavior. The effective mobility was then estimated from the linear as well as saturation regime of the I-V output characteristics, and compared to that obtained from the *C*-*f* measurements. Here can be mentioned that mobility was not a function of



Fig. 1: Output characteristics of pentacene OFET for various gate-source voltages.

the applied gate voltage in both linear and saturation region.

3. Analysis

The electric field propagation along channel in OFET was recently successfully modelled by the transmission line approximation (TLA) [1]. TLA is based on the solving of the equivalent circuit consisting of infinitesimally small resistors and capacitors connected in series as a ladder. Therefore again, the resistor R and capacitor C are related to the distribution of the electric field and accumulated charge, *i.e.*, $Q_s(x) = CV(x)$. In other words, charging of the capacitors C represents migration of the charge and resistance R describes potential drop across the channel. Here should be noted that in present model of the three-electrode system (OFET structure) we do not assume influence of injection properties, i.e. potential drop due to insufficient charge accumulation.

In following, analogous to analysis of the MIM structure the charge transport can be again solved by the relaxation times of RC loops with distributed parameters. In the linear region (drain-source voltage is smaller than gate-source voltage, $V_{ds} < V_{gs}$) the constant electric field condition should be satisfied and all resistors of the equivalent circuits have identical value. Therefore transit time can be written as a product of the total channel resistance R_{ch} and capacitance C_{ch} , i.e., $t_{tr} = R_{ch}C_{ch}$. In the linear region the drain-source current I_{ds} can be expressed as follows

$$I_{ds} = C_g \frac{W}{L} \left(V_{gs} - V_{th} \right) V_{ds} \tag{1}$$

where C_g is gate insulator capacitance per unit of area, W/L is channel width/length and $V_{gs} - V_{th}$ is applied gate-source voltage, V_{gs} , reduced by the threshold voltage, V_{th} . Hence, the channel resistance is derived,

$$R_{ch} = \frac{\mathrm{d}V_{ds}}{\mathrm{d}I_{ds}} = \frac{L^2}{C_g W \mu (V_{gs} - V_{th})} \tag{2}$$

and channel capacitance is

$$C_{ch} = C_g WL \tag{3}$$

where WL represents channel area. Therefore, the transit time can be written as a product of Eq.(2) and (3) in form

$$t_{tr} = R_{ch}C_{ch} = \frac{1}{\mu} \frac{L^2}{(V_{gs} - V_{th})}$$
(4)

At first we must mention carrier migration through the device with square root of time ($t \propto L^2$). This result is in accordance with our previous experiment based on the direct visualization of the electric field in the OFET [2]. However, our calculation has also other important consequences: (i) charge is propagating through the OFET channel not due to electric field between Source and Drain electrode, but as a propagation of interface charging phenomenon; (ii) charge is propagating also if there is no drain-source voltage present. In contrast to the two-electrode system represented by the MIM structure, where the transport mechanism is limited by the drift in the electric field, in the three-electrode system expressed by the OFET structure the charge is transported due to propagation of the interface charging (i.e. propagation of the accumulated charge layer).

Therefore, it can be helpful to use measurement of the frequency dependence of the capacitance. Here, the carriers are injected from the Source and Drain electrodes and accumulated on the pentacene – gate insulator interface. Thus the increase of the capacitance is related to the charge migration across the channel and can be used for the mobility evaluation. In other words, the cut-off frequency can be expressed as follows

$$f_{\max} = \frac{1}{(t_{tr} + t_{inj})}$$
 (5)

where t_{inj} stands for injection time and illustrates effect of the contact resistance R_C , *i.e.*, $t_{inj}=C_gR_C$ [3,4]. Hence, for contact resistance of ~100k Ω or higher (estimated from the transmission line method, not shown here) we can express reciprocal transit time as a linear function of the gate voltage in accordance to Eq.(4). Interestingly, the mobility obtained from the slope of the linear fit (0.08 cm²/V.s) is in good correspondence with value obtained by the I-V measurement (0.11 cm²/V.s).



Fig. 2: Voltage dependence of the reciprocal transient time, which was obtained from the C-f measurement (show in inset). Solid line represents linear fit.

Finally, we should note that the present approach is well confirmed by the direct observation transient carrier transport experiments using the time-resolved optical second harmonic generation [4].

4. Conclusion

In the end, it can be explained as the Maxwell-Wagner charging propagation, where charge transport is realized by the creation of the accumulated charge on the organic semiconductor - gate insulator interface. This result is different from the two-electrode systems (metal-pentacene-metal structures), where the charge transport can be expressed as a drift of carriers driven by the voltage applied between electrodes. On the basis of proposed model was found relationship for the transit time and applied for the capacitance measurement. Estimated carrier mobility is in good agreement with a value from the I-V experiment. This discussion point out difference in charge transport mechanism, which has an effect on the mobility evaluation from the transit time measurements, and propose capacitance measurement as an alternative method for mobility evaluation.

References

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