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# Frequency Dependence of Displacement Current and Channel Current in Pentacene Thin-Film Transistors

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## 1. Introduction

Organic thin-film transistors (OTFTs) which use organic semiconductor as active layer have attracted considerable attentions for their potentials such as low-cost, large-area, and flexible devices as well as the mobility, which is comparable to that of hydrogenated amorphous silicon (a-Si:H) TFTs.[1] For the practical use of OTFTs such as RFID or logic circuit, it is important to evaluate carrier injection properties under high frequency operation. Displacement current measurement (DCM) is a direct method to probe the carrier injection properties in organic materials.[2-5]

We have developed simultaneous measurements system of displacement current and channel current in top-contact OTFTs, which expands DCM to three terminal devices, and which enables us to understand carrier injection properties under the device operation.[6]

In this paper, we demonstrate the frequency dependence of displacement current and channel current in top-contact pentacene thin-film transistors. The frequency dependence of field-effect mobility, threshold voltage and carrier injection voltage at the source electrode are evaluated at frequencies ranging from 1 to 50 kHz.

## 2. Experiments

The detailed description of the simultaneous measurements of displacement current and channel current has been provided in our previous paper[6]: however, only a brief outline is provided here. Figure 1 shows a schematic diagram of the simultaneous measurements system of displacement current ($I_{dis}$) and channel current ($I_{DS}$). $I_{dis}$ and $I_{DS}$ are evaluated from source ($I_S$) and drain ($I_D$) currents under the applications of a triangular-wave of gate voltage ($V_{GS}$) and a constant drain voltage ($V_{DS}$). Displacement current at source ($I_{disS}$) and drain electrode ($I_{disD}$) is given by

$$I_{disS,disD} = C_{S,D}(t)\frac{dV_{GS}}{dt}, \qquad (1)$$

where $C_{S,D}(t)$ consist of capacitances of organic thin-film layer ($C_1$) and that of gate dielectric layer ($C_2$) under the source and drain electrode, respectively. In the case of the simultaneous measurements system of $I_{dis}$ and $I_{DS}$ in the OTFT structure, $I_{dis}$ and $I_{DS}$ are expressed by measured $I_S$ and $I_D$ as

$$I_{dis} = I_{disS} + I_{disD} = I_S + I_D,$$

and

$$I_{DS} = \frac{-I_S + I_D}{2}, \qquad (2)$$

respectively, when it is assumed that $I_{disS}$ is the same as $I_{disD}$. By using these equations, $I_{dis}$ and $I_{DS}$ can be evaluated from the simultaneously measured $I_S$ and $I_D$.

We use top-contact pentacene OTFTs with $SiO_2$/ polyimide dual-gate dielectric and gold electrodes in the experiments. The structure and fabrication procedures of the top-contact pentacene OTFTs have been described in our previous papers.[6,7]

The pentacene OTFTs were annealed at 400 K in nitrogen atmosphere for several hours before the measurements, and all measurements were conducted in nitrogen atmosphere. $I_S$ and $I_D$ were simultaneously measured using a digitizing storage oscilloscope (Hioki, 8855) under the applications of a constant drain voltage ($V_{DS}$) and a triangular-wave gate voltage ($V_{GS}$) in the top-contact pentacene OTFTs. $V_{GS}$ was applied as five cycles of triangular-waves with the amplitude of 30 $V_{p-p}$ at frequencies ranging from 1 to 50 kHz. During all the measurements, $V_{DS}$ was maintained at -14 V. The measurements were performed at 300 K.

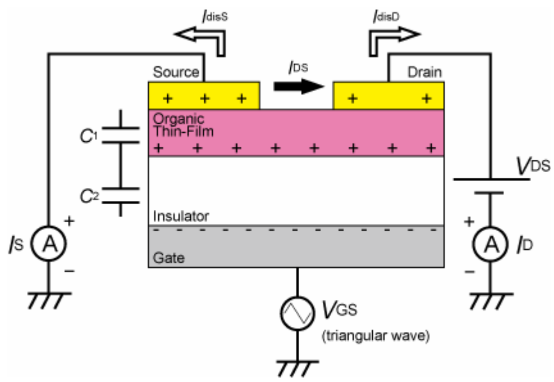


Fig. 1 Schematic diagram of simultaneous measurements system of $I_{DS}$ and $I_{dis}$ in top-contact OTFTs. $I_S$ and $I_D$ are simultaneously measured under the application of a triangular-wave $V_{GS}$ and a constant $V_{DS}$. $C_1$ and $C_2$ are the capacitance of the gate insulator layer and that of organic thin-film layer, respectively.

## 3. Results and Discussions

Figure 2 shows the typical experimental results of (a) square-root of channel current ($I_{DS}^{1/2}$) – $V_{GS}$ and (b) normalized displacement current by frequency ($I_{dis}/f$) – $V_{GS}$ characteristics at the frequencies of 1 and 50 kHz. $I_{dis}$ and $I_{DS}$ were calculated from the simultaneously measured $I_S$ and $I_D$ of the first cycle of $V_{GS}$ using eq. (2). In Fig. 2 (a), $I_{DS}^{1/2}$ – $V_{GS}$ characteristics obtained by a semiconductor parameter analyzer (Agilent, 4156C) is also plotted.

From Fig. 2 (a), the field-effect mobility (μ) and the threshold voltage ($V_{th}$) were evaluated as 0.31 and 0.30 $cm^2$/Vs, and 3.7 and 4.0 V at 1 and 50 kHz, respectively. μ and $V_{th}$ obtained by the semiconductor parameter analyzer were 0.31 $cm^2$/Vs and 3.3 V, respectively, which were in good agreement with those obtained by the simultaneous measurements. It notes that μ and $V_{th}$ at other frequencies between 1 and 50 kHz (not shown) were also identical. In Fig. 2 (b), the voltage where the displacement current at the source electrode starts to increase was defined as carrier injection voltage at the source electrode ($V_{inj}$), since pentacene thin-film acts as p-type semiconductor, carrier should be injected to pentacene thin-film/gate insulator interface below $V_{inj}$.[6] $V_{inj}$ were estimated as 12 and 11 V at 1 and 50 kHz, respectively.

From the comparison between the results at the gate voltage frequency of 1 and 50 kHz, μ, $V_{th}$ and $V_{inj}$ were identical at each frequency, which indicates that the both carrier injection and carrier transport in top-contact pentacene OTFTs can fully operate at 50 kHz. It notes that in Fig. 2 (a), the reason why there were peaks at $0 < V_{GS} < V_{inj}$ at 1 and 50 kHz is that $I_{disS}$ was not equal to $I_{disD}$ in this $V_{GS}$ range. According to eq. (1), displacement current is proportional to the gate voltage frequency, the peak at 50 kHz was seven times larger than that at 1 kHz due to the carrier injection at the source electrode.

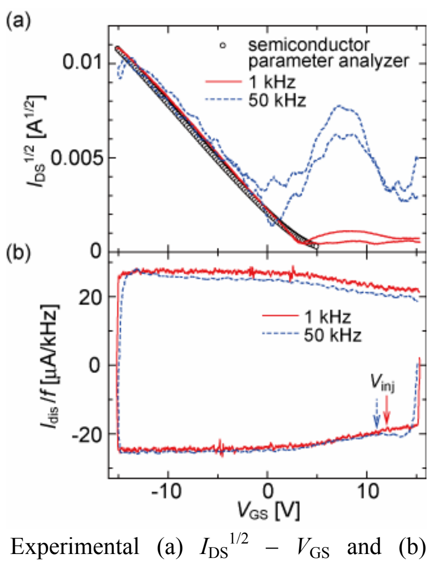


Fig. 2 Experimental (a) $I_{DS}^{1/2}$ – $V_{GS}$ and (b) $I_{dis}$ – $V_{GS}$ characteristics at gate voltage frequency of 1 and 50 kHz. $I_{DS}^{1/2}$ – $V_{GS}$ characteristics obtained by semiconductor parameter analyzer is also shown.

## 4. Conclusions

Carrier injection and carrier transport properties, such as field-effect mobility, threshold voltage, and carrier injection voltage at the source electrode were evaluated by the simultaneous measurements system of displacement current and channel current in top-contact pentacene OTFT. The simultaneous measurements system of $I_{dis}$ and $I_{DS}$ can be applied at the gate voltage frequency of 50 kHz in the top-contact pentacene OTFTs, and both carrier injection and carrier transport properties were independent of the frequency.

For the practical use of organic thin-film transistors, simultaneous measurements system of $I_{dis}$ and $I_{DS}$ is a simple and powerful technique to evaluate carrier injection properties and carrier transport properties under the high frequency device operation.

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