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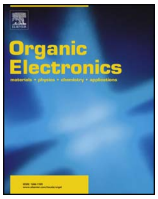

Mobility overestimation due to minority carrier injection and trapping in organic field-effect transistors

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ABSTRACT

Donor–acceptor (D–A) polymers are promising candidates as semiconductors in flexible transistors because of their high mobility. However, in recent studies on D–A polymer transistors, device characteristics deviate from the idealized transistor model, which is commonly used for extracting mobility, and show an abrupt turn-on in the drain current when measured as a function of gate voltage. To examine the validity of the reported mobility values of D–A polymers, we investigate the detailed mechanism of the nonideal electrical characteristics by device simulation based on a split-channel model, where the gate voltage swing on the drain side is higher than that on the source side. We demonstrate that minority carriers injected into low-bandgap D–A polymers (electrons in the case of usual D–A polymers) at high drain voltages and low gate voltages cause insufficient pinch off, resulting in an overestimation of mobility if the conventional mobility extraction method is used. A more reliable method for estimating mobility from the nonideal transfer characteristics is developed and applied to recent reports. It was determined that the mobility values of D–A polymers in the recent reports were overestimated by a factor of 1.7–94 or more.

1. Introduction

In recent years, donor–acceptor (D–A) alternating polymer semiconductors have been attracting significant research interest as an active layer of organic field-effect transistors (OFETs) because of their mobility, solution processability, and large-area uniformity. These characteristics are essential for realizing high-speed integrated circuits and large-area active matrix devices by low cost manufacturing processes utilizing printing techniques. The mobility of polymer semiconductors has been improving over the past decade and D–A polymers with mobilities approximately one order magnitude higher than that of conventional polymer semiconductors have been reported recently [1–22]. For example, for polymers containing diketopyrrolopyrrole (DPP) and different donor units, mobilities up to 17.8 $\mathrm{cm^2\,V^{-1}\,s^{-1}}$ have been claimed [1–15], and for cyclopentadithiophene (CDT)-thiadiazolopyridine (PT) copolymers, even higher mobilities up to 56.1 $\mathrm{cm^2\,V^{-1}\,s^{-1}}$ have been claimed [16–22].

Although the mobility values of organic semiconductors including both small molecules and polymers substantially exceed that of conventional hydrogenated amorphous silicon (a-Si:H) semiconductor (0.5–1.0 $\mathrm{cm^2\,V^{-1}\,s^{-1}}$), it has been pointed out that the reported mobility values do not reflect the true current driving capability and switching speed of the devices [23]. This is because the electrical characteristics of OFETs with high-performance organic semiconductors frequently deviate from the idealized metal-oxide-semiconductor field-effect transistor (MOSFET) model, which is commonly used for extracting mobility. Particularly, the ambipolar characteristics of low band-gap D–A polymers frequently cause a significant deviation from the idealized MOSFET model, which posits a simple carrier distribution comprising only one type of carrier in the channel. For this reason, the validity of the mobility values of high-performance organic semiconductors including D–A polymers in recent reports remains a discussion item [23–28].

The evaluation of field-effect mobilities is based on a fit to the current–voltage characteristics of a particular transistor model, which means that it is essential to apply the appropriate model for evaluating mobility rigorously. The different modes of operation of a MOSFET can be defined according to the drain voltage V_d with respect to the gate voltage swing (i.e., the difference between the gate voltage V_g and the threshold voltage V_th). The drain current of the idealized MOSFET model in the saturation ($|V_\mathrm{g}-V_\mathrm{th}| < |V_\mathrm{d}|$) and linear ($|V_\mathrm{g}-V_\mathrm{th}| > |V_\mathrm{d}|$) regimes is represented, respectively, by

$$I_\mathrm{d} = \frac{\mu C_\mathrm{OX} W}{2L}(V_\mathrm{g}-V_\mathrm{th})^2 \qquad (|V_\mathrm{g}-V_\mathrm{th}| < |V_\mathrm{d}|) \tag{1}$$

$$I_\mathrm{d} = \frac{\mu C_\mathrm{OX} W}{L}\left[(V_\mathrm{g}-V_\mathrm{th})V_\mathrm{d} - \frac{V_\mathrm{d}^2}{2}\right] \qquad (|V_\mathrm{g}-V_\mathrm{th}| > |V_\mathrm{d}|) \tag{2}$$

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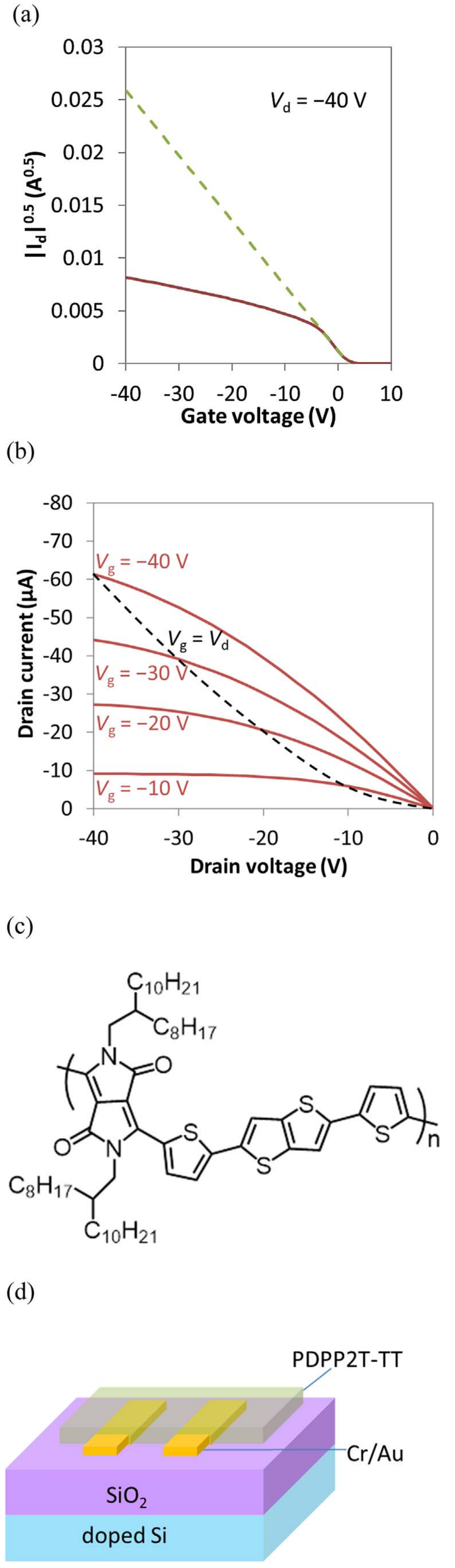

Fig. 1. (a) Transfer characteristics in the saturation regime ($V_d = -40$ V) and (b) output characteristics of a PDPP2T-TT transistor exhibiting nonideal characteristics. Black dashed line in (b) indicates $V_g = V_d$. (c) Chemical structure of PDPP2T-TT. (d) Bottom gate/bottom contact organic field-effect transistor.

where μ is the mobility of the semiconductor layer, C_{OX} is the capacitance of the gate insulating layer per unit area, W is the channel width, and L is the channel length, respectively. Here, V_{th} is assumed to be constant along the channel. Equation (1) indicates that the slope of the $\sqrt{I_d}$–V_g curve in the saturation regime is constant while the current is saturated with respect to the drain voltage. Therefore, the mobility in the saturation regime μ_{sat} is commonly extracted from the slope of the $\sqrt{I_d}$–V_g curve using the expression derived from Equation (1),

$$\mu_{sat} = \frac{2L}{WC_{OX}}\left(\frac{\partial\sqrt{I_d}}{\partial V_g}\right)^2 \tag{3}$$

Similarly, the mobility in the linear regime μ_{lin} can be extracted from the slope of the I_d–V_g curve as

$$\mu_{lin} = \frac{L}{WC_{OX}V_d}\frac{\partial I_d}{\partial V_g} \tag{4}$$

In this paper, we focus on a particular nonideal electrical characteristic observed in D–A polymer transistors shown in Fig. 1(a) and (b). The transfer and output characteristics of D–A polymer transistors in recent reports deviate from the idealized MOSFET model as follows: 1) The slope of the $\sqrt{I_d}$–V_g curves in the saturation regime is high at low gate voltages slightly above the threshold voltage and decreases with increasing magnitude of the gate voltage. Therefore, high mobility values in recent reports of D–A polymers were extracted only from considerably narrow, low gate voltage regions. 2) Insufficient saturation behaviors in the output characteristics are observed even at long channel lengths. The drain current increases with increasing drain voltage although the saturation voltage condition $|V_g - V_{th}| < |V_d|$ appears to be satisfied.

Similar transfer characteristics, where high mobility is extracted only from low gate voltage regions, were observed in OFETs with high-mobility small molecules such as rubrene single crystal [27,29] and 2,9-didecyl-dinaphtho[2,3-b:2′,3′-f]thieno[3,2-*b*]thiophene (C_{10}DNTT) [30]. The physical reason for this nonideal behavior has been explained by contact resistance that decrease more rapidly with increasing gate voltage compared with channel resistance [26,27,30]. Another explanation is that efficient charge transport is realized at lower gate voltages because the accumulation layer is not as tightly confined to the interface and extends into the bulk, where the degree of disorder is lower than that at the interface [29]. Other research groups have also proposed several possible mechanisms where the decrease in mobility at high gate voltages is attributed to charge injection into the gate insulating layer [23] or Coulombic interactions between charges [31].

Recently, we experimentally and numerically demonstrated that trapping of minority carriers is the primary cause of the appearance of the nonideal behaviors in D–A polymer transistors [25]. Minority carriers (electrons in the case of p-type transistors) are injected through relatively small energy barriers between the drain electrode and the low bandgap D–A polymers at high drain voltages. The injected minority carriers are trapped nonuniformly along the channel according to the electrical potential distribution created by the drain and gate voltages. Localized minority carriers trapped near the drain electrode induce additional mobile holes, and hence, current limitation by the pinch-off effect is reduced. Consequently, abrupt turn-on in the drain current with respect to the gate voltage is observed. Applying the conventional method for extracting the saturation mobility to the nonideal transfer characteristics obviously results in overestimation because the current in the idealized MOSFET model is limited by the pinch off at the vicinity of the drain electrode. Although we have demonstrated that the overestimation of mobility of D–A polymers is caused by an insufficient pinch off, further investigations on the detailed mechanisms of the nonideal behaviors are required for estimating intrinsic mobility and true device performance. These are crucial for developing molecular design concepts for higher mobility materials and for designing circuits.

Here, we propose a split-channel model, where the channel is