Contact effects and extraction of intrinsic parameters in poly(3-alkylthiophene) thin film field-effect transistors

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We report on contact effects in polymeric thin film transistors based on poly(3-octylthiophene) and poly(3-hexadecylthiophene) with gold contact electrodes and in the bottom contact configuration. A method to extract the intrinsic channel mobility from the measured extrinsic mobility over a broad range of gate voltage is presented. This method uses the I-V characteristics of the transistor in its reverse mode operation. The results show that the intrinsic mobility in the channel is gate voltage dependent and increases almost linearly with voltages at biases above the threshold voltage. By applying a model based on the theory of space-charge-limited conduction, the dependence of the threshold voltage on the contacts and the shifts observed in this parameter with different polymer film thicknesses are explained. We also apply this model to explain the effects of light in reducing the contact effects and changing the device parameters from extrinsic in the dark to intrinsic under illumination. © 2008 American Institute of Physics. [DOI: 10.1063/1.2942400]

I. INTRODUCTION

Polymeric and organic thin film transistors (PTFTs/OTFTs—hereafter we use OTFTs to mean both organic and polymeric transistors) have attracted considerable interest in recent years due to the significant improvement in their electrical performance and their high potential for applications such as low-cost, large-area flexible electronic systems. However, more efforts are still needed to better understand the influence of the source and drain contact metals on the transistor’s performance since they present large gate voltage dependent contact resistances that result in electrical characteristics of the OTFTs deviating from the standard silicon metal oxide semiconductor field effect transistor (MOSFET) model predictions.1–11 This is in addition to the gate-voltage influence on the intrinsic mobilities in OTFTs, which is different from that in silicon MOSFETs, as reported in many publications, for example, Refs. 12–15.

Several studies (for example, Refs. 1, 2, and 13) have shown that OTFTs with the bottom contact (BC) design demonstrate inferior performance, compared with those with the top contact (TC) design, because of higher parasitic series resistances and lower extrinsic mobilities. Also, it has been observed that the extrinsic mobility decreases with the channel length in both TC TFTs and BC TFTs due to the contact resistance effect. This can create a serious problem when using short channel length (<10 μm) transistors needed as drivers for large-area display applications, for example, since the contact resistance may become comparable to or even exceed the channel resistance.1,12–17 However, BC TFTs are preferred for fabrication of organic electronic circuits since they are easier to fabricate on a flexible substrate.1

The detection of voltage drops at the source/drain contacts by the method of scanning potentiometry has demonstrated that the transport properties of the transistor’s channel can be separated from those of the electrode contacts in a simple model.2,5,6 In TFTs with non-Ohmic contacts, such as those based on poly-9,9’-diocetyl-fluorene-co-bithiophene (F8T2) with Au contacts, a large contact resistance may appear at the source contact due to a Schottky barrier for hole injection, while for Ohmic contacts such as those in Au/ P3HT TFTs, the source and the drain contact resistances are almost identical and are governed by bulk transport through a low-mobility region close to the contact metal.7 Therefore, a general approach to modeling of OTFTs is to divide the total source/drain voltage into an intrinsic channel component and another component for the contacts.5,6

In using the standard MOSFET equations for OTFTs and obtaining a better fit for the measured data, some methods consider that the mobility and/or contact resistance are gate voltage dependent.5,13,14 For Au-sexithiophene TFTs, a method assuming a constant contact resistance and a gate-voltage dependent mobility was developed to extract the intrinsic mobility from the transfer characteristics and to estimate values for the threshold voltage and contact resistance.13,14,16 For Au-pentacene TFTs, a model incorporating a gate voltage dependent mobility and highly nonlinear drain and source contact resistances was proposed to simulate the transport characteristics.13 In Ref. 5, polymer TFTs based on F8T2, which makes a non-Ohmic contact with Au, were studied and assumed that the mobility is constant and the nonlinear current-voltage relation at the source depends on the gate voltage. The contact resistance was extracted from the output characteristics measured with transistors of different channel lengths, and the contact current was found to be exponentially related to the contact voltage.5

With the channel length scaling technique, it is possible first to obtain the contact resistance via length scaling measurements and then to remove it from mobility measure-
ments. This technique has been used for different TFTs based on different organic materials.\textsuperscript{6,7,15,16} In BC-TFTs based on poly(3-hexylthiophene) (P3HT), when Au contacts are used, it has been shown that both the mobility and the contact resistance are gate voltage dependent.\textsuperscript{5,15,17} Two difficulties with this technique of measurement are the need for a series of devices with different channel lengths and the assumption that the contact and channel transport properties in each device of different lengths are identical.\textsuperscript{3}

Contact resistance effects on the threshold voltage in short channel OTFTs have been investigated experimentally and with analytical models. It has been found that the higher the contact resistance, the larger is the threshold voltage, and therefore the extracted mobility becomes lower.\textsuperscript{17–19} In Ref. 17, a model for Au-pentacene TFTs has been proposed showing that the extrinsic threshold voltage has two components—an intrinsic component and a contribution from the contacts that depends on the film thickness.

In this paper, we present a detailed study of the electrical properties of OTFTs in the forward and reverse modes of operation, with an emphasis on the influence of the contact resistance on the field-effect mobility. We introduce a method to extract the intrinsic mobility and contact resistance, using reverse mode \textit{I-V} characteristics. The method was studied for OTFTs based on poly(3-octylthiophene) (P3OT) and poly(3-hexadecylthiophene) (P3HDT) with gold contacts and in a BC configuration. We also propose a model based on the theory of space-charge-limited current (SCLC) for the disordered region in the polymer near the contact to explain the contact effect in shifting the threshold voltage. The proposed model is also used to explain the effects of light in reducing the contact effects and changing the device parameters from extrinsic in the dark to intrinsic under illumination.

II. EXPERIMENTAL DETAILS

PTFTTs with a channel of width \(W=1.5\) cm (multifinger configuration) and length \(L=10\) \(\mu\)m were fabricated. Two identical gold electrodes (20 nm thick) were deposited onto a thermally grown silicon dioxide film (\(\sim 200\) nm) on a degenerately doped \(n\)-type Si substrate to form the source and drain electrodes. Then, two different polymers of P3HDT and P3OT with a regioregular 95\% head-to-tail ratio were deposited by spin coating at various rpm from 2 mg/ml solutions. After the formation of the polymer film, the devices were annealed in a nitrogen atmosphere at 118 °C in the absence of light and under \(N_2\) gas for 3 min. Then, the transistors were cooled very slowly (overnight) in a pure nitrogen atmosphere to room temperature and were stored in vacuum. The thickness of the polymer films was determined with an atomic force microscope (Thermo Microscope, explorer) in noncontact mode.

The \textit{I-V} characteristics, in the normal mode and reverse mode of biasing, were measured in the dark with a Hewlett-Packard 4145B-semiconductor parameter analyzer. Also, the photoinduced current in the PTFTTs under broadband white-light illumination from a halogen lamp through a microscope were measured and the \textit{I-V} characteristics were obtained.

III. CHARGE TRANSPORT MODEL

A. Normal mode of transistor operation

Since polythiophene-based TFTs are \(p\)-channel transistors, they operate in the normal mode when the drain and gate voltages are both negative with respect to the source (\(V_{DS}\) and \(V_{GS}\)). To consider the effects of contact resistances, we use a simplified low-frequency model, where the conducting path between the source and drain is divided into a series of three resistive elements: the source contact resistance \(R_s\), the drain contact resistance \(R_d\), and the gate-modulated channel resistance \(R_{ch}\). The resistance due to the injection process at the source is considered to be negligible since the Schottky barrier is low when Au electrodes are used.\textsuperscript{2} Therefore, \(R_s\) and \(R_d\) arise only from bulk transport through defect-rich regions near the contacts where the density of the trapped carriers is high and no-accumulation layer forms. The length of this low-mobility region is around 100 nm and its resistance is controlled by the gate bias voltage.\textsuperscript{2} Also, the channel resistance, which is related to the accumulation layer of charges at the interface with the insulator, is controlled by the gate bias voltage but the contact resistance \(R_C\) (where \(R_C=R_s+R_d\)) is independent of the channel resistance.

With the above model, there is a voltage drop of \((V_{DS} − V_C)\) across the main channel, where \(V_C\) is the voltage dropped across a contact resistance \(R_C\). By using the gradual-channel approximation and after integration of the potential along the channel, the following equation is obtained for the current-voltage behavior:\textsuperscript{5,6}

\[
I_{D,neq} = -\frac{W\mu C_i}{(L - d)}[(V_{GS} - V_{AT})(V_{DS} - V_C) - 0.5(V_{DS}^2 - V_C^2)],
\]

where \(L\) is the total channel length, \(d\) is the length of the depleted region at the contact, \(W\) is the channel width, \(C_i\) is the gate capacitance per unit area, \(\mu\) is the intrinsic mobility, and \(V_{AT}\) is the apparent threshold voltage that is expected to contain a contribution from the contact. Since the channel length is long, \(L=10\) \(\mu\)m in our devices, then we can justifiably neglect \(d\) (\(\sim 100\) nm) in Eq. (1). To simplify this equation, we will replace \(V_C\) by \(\alpha V_{DS}\), where \(\alpha = R_s/(R_{ch} + R_C)\) is defined for devices with Ohmic contacts. Note that \(V_{AT}\) and \(V_C\) in Eq. (1) are negative values because they correspond to the signs of \(V_{GS}\) and \(V_{DS}\), respectively.

B. Reverse mode of transistor operation

The polymer-based TFTs operate in the reverse mode if the drain voltage \(V_{DS}\) is positive and the gate voltage \(V_{GS}\) is negative. This means that the drain in the normal mode \((V_{DS} < 0)\) becomes the source in the reverse mode \((V_{DS} > 0)\) and the effective gate voltage changes to \(V_{GD} = (V_{GS} + V_{SD})\), where \(V_{GS}\) and \(V_{SD}\) are negative. Therefore, the gate voltage is not fixed as \(V_{DS}\) changes. The current-voltage characteristics in the reverse mode can be described by the following equation:
In the reverse mode of operation ($V_{DS} > 0$ V), when $V_{GS} = 0$ V, the $I_D-V_{DS}$ characteristics can be explained using our proposed model in Fig. 1. As shown in this figure, the drain electrode is now acting as a source. This is because the gate, with respect to the drain, is biased by $V_{SD} = -V_{DS}$ while the gate to source is zero. Therefore, all traps in the low-mobility region close to the drain can be filled by the induced charges due to the gate bias, while the low-mobility region near the source remains the same unless the filling of the traps is achieved by a high electric field from $V_{DS}$. Then, the trap-filled voltage $V_{TF}$ determines a current at which the conduction becomes Ohmic, but the SCLC at $V_{DS} < V_{TF}$ is proportional to $(V_{DS})^n$, where $n$ is much greater than 1 at low $V_{DS}$ and decreases to 2 at $V_{DS} = V_{TF}$. This is mainly due to trap charging of the low-mobility region that increases the conduction strongly with $V_{DS}$. Therefore, for the SCLC, a turn-on voltage $V_{on(0)} \approx V_{TF}$ can be defined and extracted by fitting the measured current with $I_D \propto (V_{DS} - V_{on(0)})^2$ or an apparent threshold voltage can be defined and extracted by fitting the data with a linear $I-V$ characteristic, i.e., $I_D \propto (V_{DS} - V_{AT})$. As a result, it can be shown that $V_{AT} = V_{on(0)} + |V_T|$, where $|V_T|$ is the intrinsic threshold voltage.

It should be emphasized that at $V_{DS} = V_{TF}$, the organic material is expected to be destroyed (breakdown) by a high applied electric field if the breakdown occurs inside the whole space between the source and drain. Moreover, for this case, $V_{TF}$ would be very large. However, in our model $V_{TF}$ is not large since the high electric field appears across a narrow region with the length of $d$, as shown in Fig. 1, and also the current is limited by the channel resistance.

At $V_{DS} > V_{on(0)}$, holes are mainly transported through the accumulation layer and the contact resistance in order to reach from the drain electrode to the source. To find the trap-filled voltage, we need to apply a model of SCLC. We use the model of gap type introduced in Ref. 28 since it is developed for thin semiconductor layers between two knifelike contacts. As Fig. 1 shows, the defect-rich region with length $d$ has a knifelike contact with the channel (hole accumulation layer) in one side and a plate metal contact (for which the area is determined by the thickness of polymer) on the other side. Changing the thickness affects mainly the total traps in this region and has no effect on the capacitance across $d$ since the thickness of the hole accumulation layer is independent of the polymer film thickness. According to the model in Ref. 28, the current-voltage characteristics is given by

$$I_{D,sub} = \frac{2W}{\pi} \mu_C e \frac{V_{DS}^2}{d^2},$$  \hspace{1cm} (3)
IV. RESULTS AND DISCUSSION

Figure 2 shows the transfer characteristics of P3HDT-TFTs at various $V_{DS}$ measured in the normal mode of operation. The inset figure shows the corresponding output characteristics at various $V_{GS}$. To extract the apparent threshold voltage $V_{AT}$ and the field-effect mobility $\mu_{FET}$, it is common to fit the data measured in the saturation by the standard FET equation that explains that the saturation current is $\approx \mu(1-\alpha)^2(V_{GS}-V_{AT})^2$. For best fitting, we find approximately $V_{AT} = -6$ V and $\mu_{FET} = 5.5 \times 10^{-5}$ cm$^2$/V s. However, these results are not accurate since the apparent mobility $\mu(1-\alpha)$ is gate voltage dependent. In Fig. 2 we have also plotted the reverse mode $I-V$ curve at $V_{GS} = 0$ V. The current data can be fitted by $I_D \approx \mu(1-\alpha)^2(V_{DS} - V_{on(0)})^2$. Since the device is symmetric, these two curves is expected to overlap if $\alpha = 0$. Therefore, there is no complete overlap due to $\mu(1-\alpha)^2 < \mu(1-\alpha)$. This is due to the differences in trap charging by $V_{GS}$ (in the saturation) and that by $V_{DS}$ (in the reverse mode biasing with $V_{GS} = 0$ V).

Figure 3(a) shows the output $I-V$ characteristics for P3HDT-TFTs in the reverse mode of operation for various negative $V_{GS}$. In this mode, the current continuously increases with the drain voltage, and no saturation regime is observed. As shown, for small negative gate voltages below $-6$ V, the characteristic is nonlinear and have different turn-on voltages depending on the value of $V_{GS}$. However, at large negative gate voltages (above $-6$ V), a transition from linear to nonlinear behavior occurs, as expected from FET currents in the reverse mode of operation.

The curves in Fig. 3(a) are redrawn in Fig. 3(b) with respect to $(V_{GS} - 6)$, where $V_{on} = |V_{GS}| + V_{DS}$ is the effective gate voltage dependent mobility. (c) Redrawn $I-V$ curves in log scale to show the details.

The value of $N_S$ can be extracted from Eq. (4), when $V_{TF}$ is measured. $N_S$ depends on the film thickness $t$ with $N_S = N_A t$, where $N_A$ is the density of empty traps in the defect-rich region. Therefore, it is expected $|V_{AT} - V_{on(0)}| + |V_{TF}|$ to increase with the polymer film thickness.
gate voltage and $V_{AT} = -6$ is chosen. As a result, the $I-V$ curves from $V_{GS} = 0$ to $-6$ V are aligned on top of each other. This is described as a pure shift of the curves with the turn-on voltages. However from $V_{GS} = -8$ V to $V_{GS} = -18$ V, the $I-V$ curves at low $V_{DS}$ become separated since the slope of the linear term increases with $|V_{GS}|$, but at larger values of $V_{DS}$ and $|V_{GS}|$, the curves are closer and cross each other since the mobility increases with $V_{GS}'$.

In Fig. 3(c), the curves of Fig. 3(a) are redrawn in logarithmic scale. By using this figure and Eqs. (3) and (4), we explain the electrical behavior of the low-mobility region at low bias voltages based on the theory of SCLC. As the figure shows, at $V_{GS} = 0$ V, the current is proportional to $(V_{DS})^3$ at low $V_{DS}$ biases, where $n = 6$. The slope decreases to $n = 2$ at $V_{DS} = 12$ V and then increases to a slope higher than 2. This curve, up to $V_{GS} = 12$ V, demonstrates the $I-V$ characteristics of the low-mobility region at the source contact since the depletion at the drain disappears at low $V_{DS}$ according to the model in Fig. 1. Therefore, a trap-filled voltage of $V_{TF} = 12$ V is found from the $I-V$ curve at $V_{GS} = 0$ and the slope of 2 at this point is due to the nonlinear conduction of the device in the reverse mode of operation at large $V_{DS}$. Figure 3(c) shows that the bulk current at this point is $\sim 32$ nA. By using Eq. (4), a value of $1.3 \times 10^{-12}$ cm$^{-2}$ is calculated for $N_0$ when $V_{TF} = 12$ V. This is equivalent to a bulk trap density of $N_B = 1.3 \times 10^{18}$ cm$^{-3}$ at zero field (i.e., $V_{DS} = 0$ V). Also, by measuring the current at $V_{DS} = 12$ V and $V_{GS} = 0$ and using Eq. (3), the mobility near the contact $\mu_c = 1 \times 10^{-5}$ cm$^2$/V s is obtained. This mobility is expected to drop to much lower values at $V_{DS} < V_{TF}$ since $\mu_0 = \theta_\mu_c$, where $\theta$ is the fraction of the total charges free to move and $\mu_0$ is the mobility at zero field (i.e., $V_{DS} = 0$ V).$^{26}$

Figure 3(c) shows that by increasing the negative bias of $V_{GS}$, the conductivity in the low-mobility region of the model, shown in Fig. 1, increases and therefore $V_{TF}$ drops. For example, $V_{TF}$ drops to 6 V when $V_{GS}$ changes from 0 to $-6$ V. The slope at this point is $\sim 1$, showing that the linear conduction is reached. Note that at larger $V_{DS}$, the conduction becomes nonlinear again as expected by the nonlinear conduction of the device in the reverse mode of operation and thus the slope increases to 2. In Fig. 3(c), the curve at $V_{GS} = -18$ V demonstrates the characteristics of the MOSFET in the reverse mode biasing, i.e., the slope is 1 at low $V_{DS}$ and 2 at large $V_{DS}$.

To extract $\mu$ vs $V'_{GS} = |V_{GS}| + V_{DS}$, we use the data in Fig. 3(a) and obtain the solution of Eq. (2) for $\mu(1-\alpha)$ and $\mu(1-\alpha)^2$. At a small and fixed $V_{DS}$ (e.g., 2 V), the second term of Eq. (2) is eliminated and $\mu(1-\alpha) vs V'_{GS} = (V_{GS} - 2) is extracted from the linear term. The results show that the apparent mobility, $\mu(1-\alpha)$, continuously increases with $V_{GS}'$. The second term in Eq. (2) is used to extract $\mu(1-\alpha)^2 vs V_{GS}' = V_{DS}$ by choosing $V_{GS} = 0$ V. The variations in $\mu(1-\alpha)$ and $\mu(1-\alpha)^2$ with $V_{GS}'$ are shown in Fig. 4. Two curves for $I_D vs V_{GS}'$ are also drawn in this figure for the two different bias combinations: $V_{DS} = 2$ V with variation of $V'_{GS} = |V_{GS}| + 2$ and $V_{GS} = 0$ V with variation in $V'_{GS} = V_{DS}$. It is noted that the two parameters $\mu(1-\alpha)$ and $\mu(1-\alpha)^2$ are extracted from the different part of the graph in Fig. 3. However, both are related to the same range of the effective gate voltage and thus to same $\mu$.

Figure 5 shows $\mu$ and $(1-\alpha)$ as functions of $V_{GS}'$. It is concluded that the intrinsic field-effect mobility is gate voltage dependent and behaves almost linear at above the threshold voltage. This is similar to the results reported in Ref. 14 for OTFTs based on oligothiophene and the result in Ref. 12 for pentacene TFTs where long channel devices have been used to eliminate the effect of contact resistance. Also, it agrees with the result in Ref. 20 for an effective mobility in disordered semiconductors described by generalized transport band definition and its extension to hopping transport.

It should be noted that in our method, the intrinsic mobility $\mu$ is assumed to be voltage independent. In the case of a voltage dependent intrinsic mobility, this method cannot separate $\mu(V_{DS})$ from $\mu(V_{GS})$ since the effective gate voltage consists of both $V_{DS}$ and $V_{GS}$. Also it should be noted that our
method is valid for devices with Ohmic contacts due to the assumption of a linear relationship between contact resistance and channel resistance. Simplified Eq. (2) (used in our method) is obtained by assuming that $R_c$ is Ohmic and the Schottky barrier at the contact is negligible. In the case of presence of Schottky barriers at the contacts, the accuracy of our method would deteriorate.

Figure 6(a) shows the diodelike characteristics of three devices based on P3OT-TFTs in the reverse mode of operation at $V_{GS}=0$ V, for three different polymer film thicknesses: $t_1=7$ nm, $t_2=13$ nm, and $t_3=38$ nm. We conclude from Eq. (2) that $I_D=(W/C/L)\mu(1-\alpha)(V_{DS})^2$ explains the electrical behavior at low $V_{DS}$, where $V_{AT}=V_{on(0)}+V_T$, and $V_T=1.5$ V. We extract $V_{on(0)}$ from the square root of $(\sqrt{I_D} V_{DS})$ and then calculate $V_{AT}$. The results are 2.5 V for $t_1=7$ nm, 3.5 V for $t_2=13$ nm, and 7.5 V for $t_3=38$ nm in P3OT-TFTs, and it is concluded that $V_{AT}$ increases with the film thickness due to the change in trap-filled voltage. This is similar to the result obtained for the threshold voltage in the normal mode in pentacene TFTs. It is also concluded that the shift of $V_{AT}$ (or the shift of $V_{TP}$) with the polymer film thickness is accompanied by some changes in the surface trap density $N_s$ given by Eq. (4). Table 1 shows the results for the three different polymer film thicknesses. $N_s$ is calculated based on a bulk trap density of $N_B=10^{18}$ cm$^{-3}$.8

At $V_{GS}=-10$ V, the linear relation of $I_D(V_{DS})$ at low $V_{DS}$ in Fig. 6(b) shows that $R_c$ is Ohmic. Based on Eq. (2), $I_D=(W/C/L)\mu(1-\alpha)(V_{DS})^2$ and the differences in slopes, for the three different thicknesses, are mainly due to the differences in their threshold voltages.

Figure 7 shows the light effect on the I-V characteristics of P3HDTS-TFTs in the reverse mode of operation when the device is under illumination of white light with an irradiance of 1.5 mW/cm$^2$. The I-V characteristics in the dark are also given for comparison. We conclude that the light mainly affects the contact region conduction, similar to the effect of $V_{GS}$ in reducing the contact resistances, while the light has no effect on the intrinsic mobility in the channel. As discussed in Ref. 9, the defect-rich regions close to the Au contacts are the photocentral sites and it is the photogeneration of charges and the trap charging in these regions that decrease the contact resistance and its effect on mobility due to $(1-\alpha)$. It reduces the trap-filled voltage, which in turn leads to the reduction of the apparent threshold voltage to the intrinsic value. Therefore, the large increase in current under an irradiance of 1.5 mW/cm$^2$ (Fig. 7) can be explained by using Eq. (2), in which $|V_{AT}|$ drops from 7.5 V in the dark to $\sim 1.5$ V under the illumination and $\alpha$ is reduced significantly. In Fig. 7, the two I-V curves at $V_{GS}=0$ V (one in the dark and one under illumination) can be approximated as two quadratic equations $I_D=(W/C/L)\mu(1-\alpha)(V_{DS}-7.5)V_{DS}$ and $I_D=(W/C/L)\mu(V_{DS}-1.5)V_{DS}$ respectively. At $V_{GS}=-10$ V, these two curves become linear. In the dark, we have $I_D=(W/C/L)\mu(1-\alpha)(10-7.5)V_{DS}$ and under illumination we have $I_D=(W/C/L)\mu(10-1.5)V_{DS}$. Therefore, it is concluded that light changes the device parameters from apparent in the dark to intrinsic under illumination.

### Table I. Effect of polymer film thickness on $V_{AT}$ or $V_{on(0)}$ in P3OT-TFTs. $N_s$ is calculated based on bulk trap density $N_B=10^{18}$ cm$^{-3}$.

| $t$ (nm) | $N_s$ (cm$^{-2}$) | $|V_{AT}|$ (V) |
|---------|-----------------|--------------|
| 7       | $0.7 \times 10^{12}$ | 2.5 |
| 13      | $1.3 \times 10^{12}$ | 3.5 |
| 38      | $3.8 \times 10^{12}$ | 7.5 |

![FIG. 6. (Color online) Effect of film thickness on diodelike characteristics of P3OT-TFTs at $V_{GS}=0$ V. (a) $V_{on(0)}$ and therefore $V_{AT}$ shift almost linearly with the polymer film thickness. (b) At $V_{GS}=-10$ V, the total current (channel current+body current) becomes Ohmic and the three different slopes for the three film thickness are due to differences in $V_{TP}$ ($V_{on(0)}$) and $\alpha$ ($=R_c/R_m$).](http://jap.aip.org/jap/copyright.jsp)
V. CONCLUSIONS

Detailed experimental results and analysis are reported for OTFTs, with an emphasis on the influence of contact resistance on the extracted mobility from measurement data. We use the $I-V$ measurement of devices based on P3OT and P3HDT in the BC configuration and introduce a method of extracting the intrinsic mobility and contact resistance using the MOSFET model. For this method, we need to analyze the data from each transistor over a wide range of bias voltages in the reverse mode of operation. The results show that the field-effect mobility is strongly dependent on the applied gate bias. We also propose a model based on the theory of SCLC to investigate the threshold voltage and bulk current characteristic. It is concluded that the apparent threshold voltage has a contribution from the low-mobility region near the contacts. This model is used to explain the shifts observed in the threshold voltage of the devices with different polymer film thicknesses. The effect of light in reducing the contact resistance and changing the device parameters from apparent in the dark to intrinsic under illumination are also explained.

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