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Organic Field Effect Transistor Based on P3HT with Two Different Gate Dielectrics

Omar A. Ibrahim, Estabraq T. Abdullah*

Physics Department, College of Science, University of Baghdad, Baghdad, Iraq

*Corresponding author, E-mail: **estabraqtalib@sc.uobaghdad.edu.iq**

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Abstract

The electrical performance of bottom-gate/top source-drain contact for p-channel organic field-effect transistors (OFETs) using poly(3-hexylthiophene) (P3HT) as an active semiconductor layer with two different gate dielectric materials, Polyvinylpyrrolidone (PVP) and Hafnium oxide (HfO_2), is investigated in this work. The output and transfer characteristics were studied for HfO_2, PVP and HfO_2/PVP as organic gate insulator layer. Both characteristics show a high drain current at the gate dielectric HfO_2/PVP equal to -0.0031A and -0.0015A for output and transfer characteristics respectively, this can be attributed to the increasing of the dielectric capacitance. Transcondactance characteristics also studied for the three organic materials and show the HfO_2/PVP gate dielectric have higher value from the single layers which indicate the effect of dielectric capacitance, g_m=-0.5517x10^{-4}A/V, -0.9931x10^{-5}A/V, and -0.6511 x10^{-4}A/V respectively

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1. Introduction

The use of organic semiconductor have great interest because of their good facilities, light weight, easy fabrication under ambient condition at low cost [1]. The important of organic semiconductors appear in devices such as transistors[2], solar cell [3], sensor[4], light emitted diode[5] which is serve as active materials. Although, these materials typically exhibit low charge carrier mobility, poor environmental stability and short operational life time comparing with inorganic counterparts[6]. Poly(3-hexylthiophene) (P3HT) is a promising compound for industrial use among organic semiconductors. P3HT is a conjugated polymer that is widely used for hole transport in organic solar cells due to its high charge carrier mobility (0.1cm^2/V.S)[7].

Because it affects the electrical performance of organic field effect transistors, organic semiconductors are the best choice for gate dielectrics in FETs [8, 9]. Organic gate dielectrics have recently been introduced as a replacement for inorganic gate oxide-type dielectrics [10]. However, the high operation voltage up to 60V is the main limitation, where it effects the power dissipation; one of the solutions is to use high capacitance insulating materials that can effectively minimize the operating voltage. Many attempts have been made to solve this problem either by reducing the thickness of the gate dielectric or increasing the dielectric constant k, so a high capacitance gate dielectric can be achieved [11]. Many studied of high-k inorganic metal oxides have been explored, include ZrO_2 [12], TiO_2 [13], Hafnium-based oxide (HfO_2), which is interested in this work [14]. The cross-linked polyvinylpyrrolidone (PVP), which has good dielectric characteristics and a high carrier mobility of 3–5 cm^2 V^{-1}s^{-1}, is one of the most valuable organic polymers[15]. A simulation of the electrical properties of bottom gate/top source-drain contact for (p-channel) P3HT-based OFETs is presented in this paper. MATLAB simulation was used to examine the characteristics.

2. Device Structure

P3HT (p-channel) OFET with configuration of bottom-gate/top contacts with 50nm thickness was studied. The channel dimension of width (W) and length (L) were 2.1 µm and 1 µm respectively. Fig. 1 shown the structure of P3HT-based OFETs. The gate dielectrics were HfO_2 (K=25) and PVP(K=4.5) layer with a 100-nm-thickness.

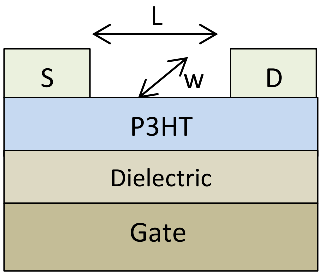

Fig.1: Schematic of P3HT based OFET.

3. Characterization Using Matlab Simulation

According to the IEEE1620-2008 Standard for OFETs Characterization [16], the approach for extracting parameters such as mobility, threshold voltage, switching ratio, and contact resistance would be derived using traditional MOSFET transistor theory. Drain current (I_d) in the linear region is given by a standard field-effect transistor model[16].

$$\mathbf{I_d = \frac{WC_i}{L}\mu \times \left[(V_g - V_T) \times V_d - \frac{V_d^2}{2}\right]} \qquad \text{….1} \qquad \textbf{with } \boldsymbol{V_d < V_g - V_T}$$

The following equation is used to simulate the current in the saturation regime due to the accumulation layer's "pinch-off":

$$\mathbf{I_d = \frac{WC_i}{2L}\mu_{\mathit{sat.}} \times \left(V_g - V_T\right)^2} \qquad \text{……….2}$$

Where μ is the mobility, V_T is the threshold voltage which equals to 5 $cm^2/V.s$ and 2.5V respectively. The transconductance in linear and saturation region of the OFET is given by[17]

$$\mathbf{g_m = \frac{\partial I_d}{\partial V_g} = \mu C_i \frac{W}{L} V_d} \qquad \text{…….3} \qquad \text{the linear region}$$

$$\mathbf{g_m = \frac{\partial I_D}{\partial V_g} = \mu C_i \frac{W}{L}.\left(V_g - V_T\right)} \qquad \text{…….4} \qquad \text{the saturation region}$$

C_i is the dielectric layer capacitance, V_g is the gate voltage, V_d is the drain voltage. These two equations, on the other hand, are valid if the field along the channel is much lower than the field across it (gradual channel approximation) and the mobility is constant. MATLAB simulation was utilized to obtain metrics such as mobility from the electrical characterization of P3HT-based OFETs.

4. Results and discussion

4.1 Output Characteristics

Figures 2,3 and 4 show the output and transfer characteristics of OFET-based P3HT for PVP and HfO_2 as organic insulator layer respectively. When negative gate voltages are applied, the device displays a typical field-effect transistor (FET) output curve, indicating that only holes accumulate at the semiconductor-dielectric interface and current flows from the source to the drain through the channel area. As a result, the OFET is operated in accumulation mode with rising negative drain current in the p-channel. The output characteristics can be discriminated between the linear, pinch-off, and saturation regimes, indicating that the P3HT and both source and drain electrodes have a good ohmic contact [18]. In Fig.3, I-V curves indicate good linearity at lower voltages. As previously stated, this demonstrates that a good ohmic contact was made between the P3HT and gold electrodes. When HfO2 insulator is used instead of PVP insulator, the drain current improves. This can be due to an increase in effective capacitance Ci, which is defined as[19][20]:

$$C_i = \varepsilon_\circ \varepsilon / t \qquad \ldots\ldots..5$$

which the carrier charge density increasing too

$$Q = C_i(V_g - V_T) \qquad \ldots\ldots6$$

Fig.4 shows more increaser in the I_d for HfO_2/PVP comparing with PVP and HfO_2, because increasing of the dielectric capacitance C_{total} , which is given by equation (7):

$$C_{total} = C_{PVP} + C_{HfO2} \qquad \ldots\ldots..7$$

The highest current can be obtained for HfO_2/PVP of OFETs is I_d = -0.0031A at V_g =-40V. These high values of the drain current can be associated with the high capacitance of the HfO_2/PVP layer.

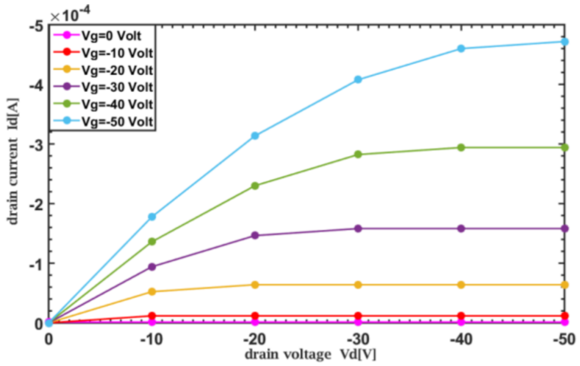

Fig.2: output characteristic of gate insulator PVP

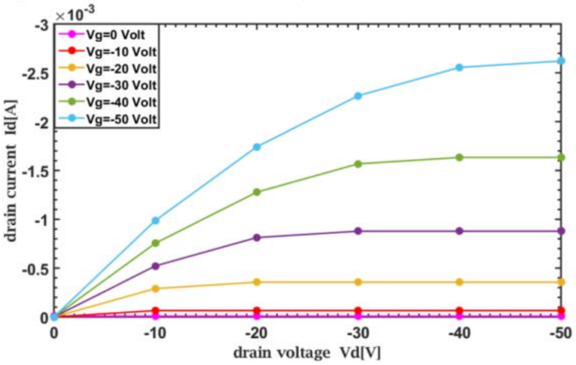

Fig.3: Output characteristic of gate insulator HfO_2

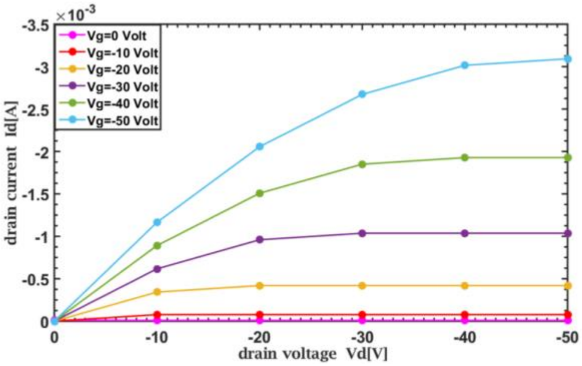

Fig.4: Output characteristic of gate insulator HfO_2/PVP.

4.2 Transfer characteristics

The typical transfer characteristics of OFETs based on PVP, HfO_2, and HfO_2/PVP dielectrics are shown in Fig 5, with V_g ranging from 0 to -50V, V_d = -50V, and thickness =100nm. Devices clearly show typical p-type transistor transfer behavior. The drain field lowers the source to channel barrier as the drain bias increases, which raises the charge carrier Q, at the beginning of the channel, and they will cross the barrier, this will eventually result in an increase in drain current. The best values of the drain current are gotten for dielectric material (HfO_2/PVP) comparing with PVP and HfO_2. The highest value of the drain current for HfO_2/PVP dielectric of OFETs was obtained in this case I_d=-0.0015A at Vg=-40V. A decrease in the drain current for all gate voltages comparing with the highest value of the drain current at Vg=-50V, is due to the threshold voltage shift only.

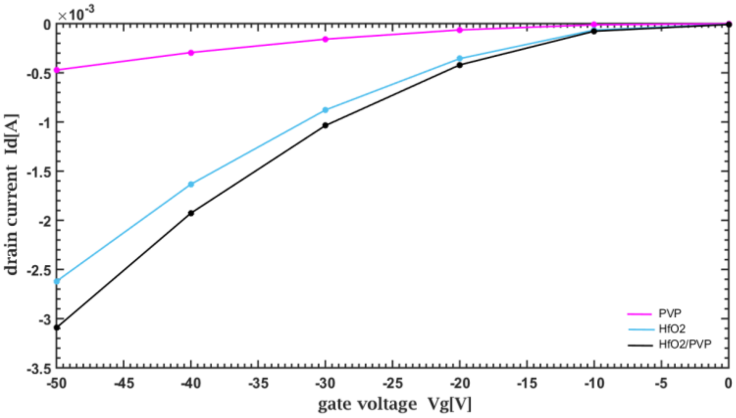

Fig. 5: Transfer characteristics of OFETs with a gate insulator thickness of 100nm at a drain voltage of -50V.

4.3 Transcondactance characteristics

P3HT OFET transconductance as a function of gate voltage is shown in Fig.6. At Vg= 0V for gate insulator HfO_2, PVP and HfO_2/PVP high transconductance is estimated to equal g_m =-0.5517x10^{-4}A/V, -0.9931x10^{-5}A/V, and -0.6511 x10^{-4}A/V respectively. When comparing HfO_2 insulator to PVP insulator, the transconductance improves, whereas the best values of transconductance are obtained for dielectric material (HfO_2/PVP) when comparing PVP and HfO2.

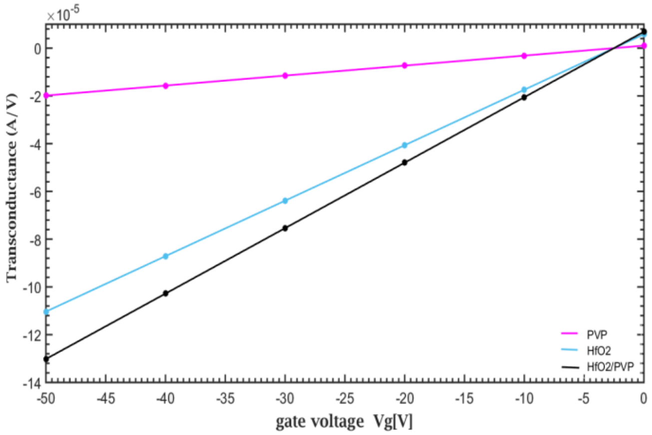

Fig. 6: Transconductance of gate insulators PVP, HfO_2 and HfO_2/PVP.

Charge carrier density, electric field, temperature, dielectric constant, and manufacturing technique all have a role in influencing device performance in electronics. Two physical processes may be used to explain the drain-source current's dependence on the dielectric constant: The gate bias causes charge carrier induction in organic semiconductors, while the source/drain electrodes produce charge carrier injection. Because an increase in capacitance generates more charge carriers at the same gate voltage, the drain-source current increases as the dielectric constant increases. Furthermore, for the same gate-source voltage, the vertical electric field increases with a higher dielectric constant, resulting in more holes injected from the source electrode. Because it must maintain its insulating ability to operate as the gate dielectric layer in OFETs, the gate dielectric cannot be too thin [21, 22].

Conclusions

OFETs having active layers of Poly(3-Hexylthiophene) (P3HT) and insulating layers of PVP and HfO2 were studied. It has been established that the device's performance is influenced by the type of gate insulator used. The electrical properties of the devices decline as the dielectric gate HfO2/PVP is increased, although it outperforms PVP and HfO_2 in terms of device performance and current density.

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ترانزستور تأثير المجال العضوي على أساس P3HT مع اثنين من عوازل البوابة المختلفة

عمر عدنان ابراهيم، استبرق طالب عبدالله

جامعة بغداد/كلية العلوم/قسم الفيزياء

المستخلص

تم في هذا العمل دراسة الأداء الكهربائي البوابة السفلية /ملامسة العلويه تصريف- المصدر للترانزستورات ذات التأثير الميداني العضوي للقناة نوع pباستخدام بولي (3-هيكسيل ثيوفين) (P3HT) كطبقة أشباه موصلات نشطة مع مادتين عازلتين مختلفتين للبوابة ، بولي فينيل بيروليدون (PVP)) وأكسيد الهافنيوم (HfO2). تمت دراسة خصائص الإخراج والنقل لـ HfO2 و PVP و HfO2 / PVP كطبقات عازلة بوابة عضوية. تُظهر كلتا الخاصيتين تيار تصريف عالي عند بوابة عازل HfO2 / PVP يساوي -A0.0031 و -A0.0015 لخصائص الإخراج والنقل على التوالي ، ويمكن أن يُعزى ذلك إلى زيادة سعة العزل الكهربائي. تمت دراسة خصائص الموصلية التحويلية أيضًا للمواد العضوية الثلاثة وأظهرت أن عازل بوابة HfO2 / PVP له قيمة أعلى من الطبقات المفردة مما يشير إلى تأثير السعة العازلة ، gm = -0.5517x10-4A / V، -0.9931x10-5A / V و -0.6511 x10-4A / V على التوالي.