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Effect of Organic / Inorganic Gate Materials on the Organic Field-Effect Transistors Performance

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Abstract

The choice of gate dielectric materials is fundamental for organic field effect transistors (OFET), integrated circuits, and several electronic applications. The operation of the OFET depends on two essential parameters: the insulation between the semiconductor layer and the gate electrode and the capacitance of the insulator. In this work, the electrical behavior of a pentacene-based OFET with a top contact / bottom gate was studied. Organic polyvinyl alcohol (PVA) and inorganic hafnium oxide (HfO_2) were chosen as gate dielectric materials to lower the operation voltage to achieve the next generation of electronic applications. In this study, the performance of the OFET was studied using monolayer and bilayer gate insulators. To model and analyze a device's electrical properties, MATLAB was used. Two main parameters were studied: switching ratio (I_{on}/I_{off}) and subthreshold swing (SS), as well as the effect of dielectric capacitance on the gate dielectric materials. The PVA/HfO_2 bilayer gate dielectric gave the best results in I_{on}/I_{off} ratio, SS and transconductance of 9.05×10^{-7}, -1.52, and -4.99 $x10^{-5}$A/V respectively, which is because the dielectric capacitance has increased.

Article Info.

Keywords:
Pentacene, OFET, Polyvinyl alcohol, Hafnium Dioxide, Switching Ratio

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1. Introduction

The physics of organic field effect transistors (OFETs) has been extensively studied in an effort to improve their efficiency. Pentacene is a p-type aromatic hydrocarbon. It is one of the most promising organic semiconducting materials due to its high mobility. Academic and industrial interest in OFETs has risen in recent years because they can be used in a variety of applications [1, 2]. For example, they can be used to make bio, gas, and optical sensors; radio frequency identification; intelligent electronic tags, and digital circuits [3]. Four possible structures are available for OFETs, including: bottom gate/bottom contact, bottom gate/top contact, top gate/bottom contact, and top gate/top contact. Bottom gate/top contact is the best structure for OFET because of the increase in drain current and mobility [4]. The gate dielectric is a crucial transistor functional layer that isolates the semiconductor transport layer from the conductive gate electrode. The dielectric layer not only regulates the amount of charge carriers in the active channel in response to an applied voltage, but it also controls electrical isolation by controlling the capacitance of the gate dielectric layer [5]. The quality of the dielectric material has an important impact on transistor properties such as gate leakage current, operation voltage, switching current ratio, threshold voltage, and mobility. Many software programs, such as MATLAB [6] and ATLAS [7], among others, were used to study their optimization and numerical simulation.

In the past few years, many studies have been carried out on FETs with inorganic-organic hybrid materials as the dielectric layer; these can be used to make thin-film and flexible optoelectronic devices of low cost such as thin-film transistors (TFTs), solar cells, photonic devices, and others [8]. Inorganic dielectrics have a number of advantages, but polymer dielectrics, which are used in translucent transistors and flexible displays, have a number of advantages over inorganic gate dielectrics. They are a practical approach to reducing the operating voltage and realizing next-generation flexible electronic uses [9]. Polyvinyl alcohol (PVA) is a water-soluble polymer; its dielectric constant (K) varies between 5-8 [10]. Oxide dielectrics have been extensively used in transistor devices because of their high density, high capacitance, and low leakage current density [11-13]. Hafnium oxide (HfO_2) as a dielectric material was given more attention, because of its excellent performance, such as a larger dielectric constant, a high band gap, and thermal stability [14].

In this study, the electrical characteristics of top contacts / bottom gate for (p-channel) pentacene-based OFET were investigated using hybrid organic/inorganic (PVA and HfO_2) gate dielectric materials as monolayer and bilayer to improve the performance of OFET; MATLAB modeling was used to extract the electrical properties.

2. Device Structure

The structure of an OFET based on pentacene is depicted in Fig.1 using a top contact / bottom gate arrangement. The structure parameters of the transistor for the simulation were chosen according to the experimental data of the reference specified in the table. Silicon was proposed for the substrate and also for the gate contacts. The source and drain electrodes were proposed to be made of gold (Au).

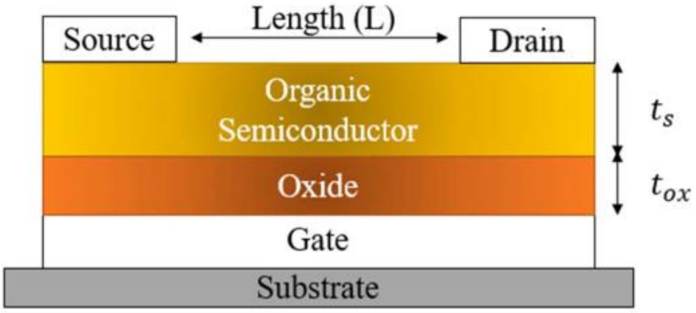

Figure 1: Pentacene based OFET device structure [14].

3. Simulation

In the direct area, I_d is calculated using the typical model of field-impact transistors [14]:

$$I_d = \frac{WC_i}{L}\mu \times \left[(V_g - V_T) \times V_d - \frac{V_d^2}{2}\right] \qquad \text{With } V_d < V_g - V_T \qquad (1)$$

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

The linear and saturation regions of transconductance curve of the OFET are described according to the given equations [18]:

$$g_m = \frac{\partial I_d}{\partial V_g} = \mu C_i \frac{W}{L} V_d \qquad \text{The Linear region} \qquad (3)$$

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

where: W, L, C_i, V_g, V_d, μ are the channel width, channel length, dielectric layer capacitance, applied voltage, the source-drain voltage, and the mobility, respectively.

4. Results and Discussion

Simulation results using MATLAB gave the OFET output and transfer characteristics shown in Figs. 2 and 3, respectively, with PVA, HfO_2, and PVA / HfO_2 bilayer dielectric materials for different values of gate voltage (V_g). The general behavior of the output characteristics shows a linear region for small values of drain voltage (V_d), which indicates that the holes are accumulated at the interface between the semiconductor and the gate dielectric; the current flows from source to drain through the channel according to the value of V_g. At the point when V_d is equal to V_g-V_T (where V_T is the threshold voltage), the saturation region begins, and the drain current saturates because of the reduction of the electric field, which leads to a pinch off in the channel. In this region, the drain current becomes independent of the drain voltage; large negative drain voltages are required to achieve saturation. Such behavior indicates that pentacene-based OFETs typically operate in the accumulation mode, which means that holes are the majority carriers and are accumulated in the conductive channel [18, 19].

Fig.2c shows the improvement of the drain current when using a bilayer (PVA / HfO_2) as the dielectric material compared to that of single layers of HfO_2 and PVA, which eventually leads to an increase in charge carriers. The increase in effective capacitance C_i, which is defined in Eq. (5) [20], suggests that the bilayer is functioning as an effective gate insulator with lower gate leakage:

$$C_i = \frac{\varepsilon_\circ K}{t} \qquad (5)$$

where $\varepsilon_\circ$ is the vacuum permittivity.

$$C_{total} = C_{PVA} + C_{HfO_2} \qquad (6)$$

Our simulated results agreed with the reported experimental data shown in Table 1, which presents the main OFET parameters. The main OFET characteristics are threshold voltage V_T, effective mobility μ, subthreshold swing SS, and the I_{on}/I_{off} ratio [3]. In this work, the values of V_T and μ were obtained from experimental data.

Table 1: Physical parameter for simulation structure.

Value	Parameter	Ref.
100 μm	Channel length, L	[15]
50 μm	Channel width, W	
50 nm	Pentacene thickness, t_s	
300 nm	HfO_2 thickness, t_{ox}	[16]
150 nm	PVA thickness, t	[9]
4.4	Dielectric constant for Pentacene, K	[3]
10.4	Dielectric constant for PVA, K	[17]
25	Dielectric constant for HfO_2, K	[16]
5 $cm^2/V.s$	Mobility, μ	[3]
-2.5V	Threshold voltage, V_T	

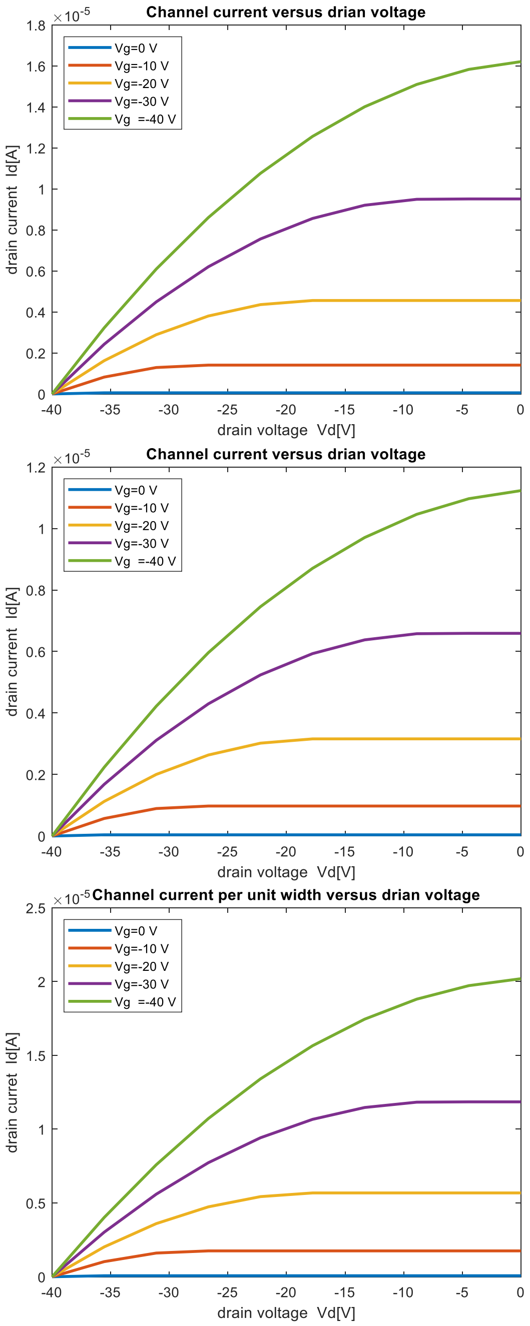

Figure 2: Output characteristic of OFET a-HfO$_2$ b-PVA c-PVA/HfO$_2$ hybrid layer.

Fig. 3 illustrates the electrical transfer characteristics of I_d vs. V_g at a constant V_d of 40V for PVA, HfO$_2$, and PVA/HfO$_2$ bilayers. Due to the fact that π-conjugated organic materials have a high resistance, they can become excellent conductors only when subjected to a relatively significant electric force field. Therefore, a material is considered effective if it permits a large drain current to pass when V_g is as low as possible.

The SS, and the I_{on}/I_{off} ratio were calculated depending on Eqs. (7) and (8) [21, 22]:

$$\frac{I_{on}}{I_{off}} = \frac{\mu}{\sigma}\frac{CV_d}{2t_s} \qquad (7)$$

where σ is the conductivity channel.

$$SS = 2.3\,\frac{KT}{q}\left(1+\frac{C_S}{C_{ox}}\right) \tag{8}$$

where: $Cs = \frac{\varepsilon_S}{x_S}$, x_S is the maximum depletion layer thickness, and ε_S is the permittivity of pentacene.

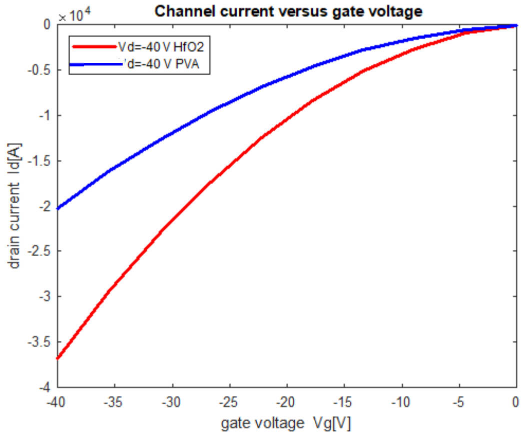

Figure 3: Transfer characteristics for PVA, HfO_2 and PVA/ HfO_2.

In general, many effective parameters that deal with the I_{on}/I_{off} ratio include the value of the dielectric constant, semiconductor thickness, and doping concentration [3]. In our work, a high ratio of I_{on}/I_{off} was achieved by increasing the dielectric constant. The calculated values of I_{on}/I_{off} and SS are shown in Table 2. Our simulation results of these two parameters agreed with the reported experimental values of the reference given in Table 2. From the table, it is clear that the transistor with a bilayer of (PVA and HfO_2) has a high I_{on}/I_{off} ratio and a low SS compared to the monolayer of the gate insulators PVA and HfO_2.

For OFET, the transconductance vs. gate voltage at a constant V_D of 40 V is presented in Fig.4. At V_g= 0V, for the insulators HfO_2, PVA and PVA/HfO_2, the transconductance g_m was calculated to be equal to $3.44x10^{-5}$ A/V, =$-1.44x10^{-5}$ A/V, and -4.99 $x10^{-5}$A/V, respectively. It can be observed that the transconductance using HfO_2 insulators is better than that of PVA, while the best values of the transconductance were obtained for the bilayer dielectric material [22].

Table 2: The main parameters results.

Dielectric Materials	**I_{on}/I_{off} ratio**	**SS**	**References**
PVA	2.77e-07	-1.41	3
HfO_2	4.98e-07	-1.48	6
PVA/HfO_2	9.05e-07	-1.52	20

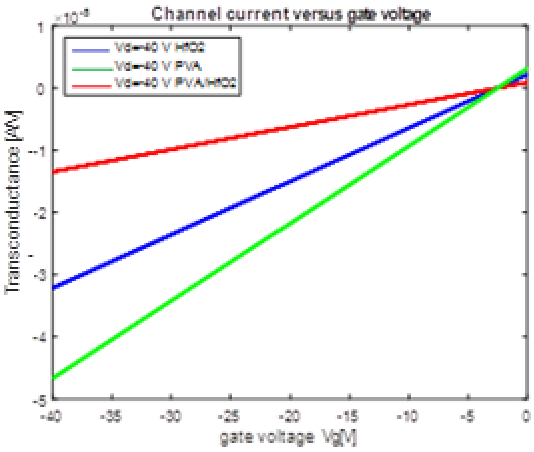

Figure 4: Transconductance characteristics for PVA, HfO_2 and PVA/ HfO_2

5. Conclusions

In this work, a simulation analysis using MATLAB software was done to study the electrical characteristics and parameters of pentacene-based OFET. Two gate insulators (PVA and HfO_2) were used as monolayers and bilayers. The bilayer showed good characteristics compared to PVA and HfO_2 monolayer gate dielectrics. The PVA/HfO_2 bilayer gate dielectric gave the best results of I_{on}/I_{off} ratio, SS and transconductance of 9.05×10^{-7}, -1.52, and -4.99 $x10^{-5}$A/V, respectively.

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Conflict of Interest

There is no conflict of interest in this research.

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تأثير مواد البوابة العضوية / غير العضوية على أداء الترانزستورات ذات التأثير المجالي العضوي

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الخلاصة

لترانزستورات هي عنصر حاسم في العديد من الأجهزة الإلكترونية. تم وصف السلوك الكهربائي لترانزستور تأثير المجال العضوي القائم على Pentacene (OFET) مع بوابة ملامسة / سفلية علوية مصنوعة من مواد عازلة للبوابة العضوية / غير العضوية في هذا العمل. تم اختيار كحول البولي فينيل (PVA) وأكسيد الهافنيوم (HfO_2) كمواد عازلة للبوابة. في هذه الدراسة، نظرنا في كيفية تأثير عوازل البوابة أحادية الطبقة وثنائية الطبقة على تشغيل OFET. لنمذجة الخصائص الكهربائية للجهاز وتحليلها، تم استخدام MATLAB. تمت دراسة معاملين رئيسيين: نسبة التبديل (I_{on} / I_{off}) وتأرجح العتبة الفرعية وتأثير السعة العازلة على المواد العازلة للبوابة. تُظهر كل من خصائص الإخراج والنقل تيارًا عاليًا للتصريف عند البوابة العازلة للكهرباء PVA / HfO_2، وذلك بسبب زيادة السعة العازلة للكهرباء. تم تحليل الموصلية التحويلية لكل من الطبقة الثنائية من HfO_2 و PVA ضد الطبقات الأحادية، وتشير النتائج إلى أن عازل بوابة PVA / HfO_2 له قيمة أعلى من الطبقة الأحادية.

الكلمات المفتاحيه: البينتاسين، ترانزستور تاثير المجال العضوي، بولي فاينيل كلورايد، هافيوم اوكسايد، نسبة التبديل.