Comparison between Horizontal and Vertical OFETs by Using Poly (3-Hexylthiophene) (P3HT) as an Active Semiconductor Layer

Bushra H. Mohammed*, Estabraq T. Abdullah
Department of Physics, College of Science, University of Baghdad, Baghdad, Iraq

Abstract

In this paper, a comparison between horizontal and vertical OFET of Poly (3-Hexylthiophene) (P3HT) as an active semiconductor layer (p-type) was studied by using two different gate insulators (ZrO_2 and PVA). The electrical performance output (I_d-V_d) and transfer (I_d-V_g) characteristics were investigated using the gradual-channel approximation model. The device shows a typical output curve of a field-effect transistor (FET). The analysis of electrical characterization was performed in order to investigate the source-drain voltage (V_d) dependent current and the effects of gate dielectric on the electrical performance of the OFET. This work also considered the effects of the capacitance semiconductor on the performance OFETs. The values of current, as calculated using MATLAB simulation, exhibited an increase with increasing source-drain voltage. Also, the organic transistor modeling software was used to evaluate the transconductance calculated. The best results for the vertical OFET were achieved using the gate insulators of ZrO_2.

Keywords: Horizontal and Vertical Organic Field Effect Transistor, P3HT, Gate Dielectric, Dielectric Constant.

مقارنه بين ترانزستور تأثير المجال العضوي العمودي والافقي باستخدام بولي الثايوفين كطبقة شبه موصل فعال

بشرى محمد حسين*، استبرق طالب عبدالله

قسم الفيزياء، كلية العلوم، جامعة بغداد، بغداد، العراق

الخلاصه

تم في هذا البحث عمل مقارنه بين ترانزستور تأثير المجال العضوي العمودي والافقي باستخدام بولي الثايوفين كطبقة شبه موصل فعال باستخدام عازلي بوابه مختلفين (اوكسيد الزركونيوم وبولي فاينيل الكحول). تم التحقق من الخواص الكهربائية باستخدام موديل تقريب القناه التجريبي. اظهرت النبطية منحنى إخراج نموذجي من ترانزستور تأثير المجال. تحليل الخواص الكهربائية أخذ للتحقق من اعتماديه فولتيه المصدر – المصرف المعتمدة على التيار بملاحظه تأثيرعازل البوابه على الاداء الكهربائي لترانزستورتاثير المجال العضوي. وتم الاخذ بعين الاعتبار تأثير متسعات شبه الموصل على اداء الترانزستور. تعرض قيم التيار المحسوبة باستخدام برنامج الماثلاب زيادة بزيادة فولتيه المصدر–المصرف. كما استخدم الموديل لاستخلاص التوصيليه. وتم تحصيل افضل النتائج باستخدام عازل البوابه اوكسيد الزركونيوم.

*Email: Bushra.hussain11@hotmail.com

Introduction

Organic field effect transistor (OFET) is one of the most fundamental devices of organic semiconductor and an important component in various applications such as the organic logic circuit, OLED driving units, and various organic sensors, etc. [1]. The performance of OFETs depends strongly on two main parameters which are the transistor geometry and material parameters. Vertical organic thin-film transistors (VOTFT) are modified of the performance restrictions of horizontal organic thin-film transistors. VOTFTs have a vertical arrangement of their components which include the gate capacitor, source electrode, organic semiconductor, and drain electrode. It can be used for different applications, e.g. super-capacitors, self-assembled source electrodes, and shadow mask patterned electrodes [2-5].

VOTFTs are characterized by high output currents at low operation voltages due to the extremely short channel lengths (in nanometer scale). While the performance of organic field effect transistors is inferior compared to that of the inorganic counterpart. Organic channel VOFETs are promising due to the short channel lengths, low cost, easy fabrication, and potential use for flexible device applications [6-10].

The molecular structures of organic semiconductors are affective on the device performance of OFETs, hence various organic semiconductor materials have been designed and synthesized. Nevertheless, the performance of OFETs relies on many important parameters includes the intrinsic characteristics of semiconductors, the properties of dielectrics and the interfacial compatibility between semiconductors and dielectrics [11-13]. The essential factors towards low voltage OFET are high relative permittivity and high resistivity. Poly (3-hexylthiophene) (P3HT) is a p-type thiophene-based polymer semiconductor that was first synthesized by Rick Mc Cullough in 1992 [14-15]. It is a π-conjugated polymer belonging to the family of polythiophenes which are obtained from the polymerization of monomer units of thiophene that is a heterocyclic compound with the formula of C_4H_4S [16, 17].

In this paper, a study of the electrical performance (output and transfer characteristics) of P3HT horizontal and vertical OFETs for the gate dielectrics (ZrO_2 and PVA) was studied by using the gradual-channel approximation model. In this paper, the effects on the performance of OFETs by the type of gate insulator, structure of the device and capacitance semiconductor was considered.

Device structure of Horizontal and Vertical OFET

A horizontal and vertical structure of OFET were used in this study. The structure of the horizontal was top contact configuration as shown in Figure-1. The used gate was Indium Tin Oxide (ITO), with a work function of φ=4.78, and gate dielectric materials were ZrO_2 and PVA. The organic semiconductor used was P3HT with gold electrodes for source and drain.
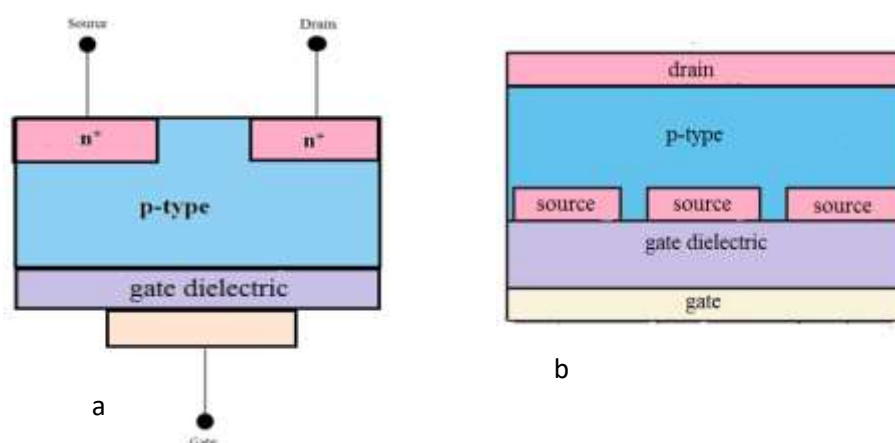

Figure 1-Structure of (a) horizontal and (b) vertical OFET.

Theory

This study supposes that the voltage varies progressively across the channel with the enforcement of voltage drain (V_d) and the gradual-channel approximation model can be utilized to describe the current flowing across the channel and extract the critical OFET operating parameters. OFETs can be operated in the linear and saturation regions, relying on the quantity of V_d relative to V_g-V_{th} where V_g

is the gate voltage and V_{th} is the threshold voltage. When no V_d is applied to the drain electrode, the positive charge carrier density is uniform across the channel. Subsequently, the source–drain current in the linear region is as follows [18]:

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

Where I_d is the drain current, W is the width, L is the channel length, μ is the mobility and C_i is the effective capacitance. $V_d > (V_g\text{-}V_{th})$ can only push the pinch-off point slightly backward toward the source electrode, and thus yield no extra current, where the current is in the saturation regime:

$$I_d = \frac{WC_i}{2L}\mu_{sat.} \times (V_g - V_{th})^2 \qquad 2$$

The transconductance in linear and saturation regions is given by [18]:

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

$$g_m = \frac{\partial I_d}{\partial V_g} = \mu C_i \frac{W}{L}(V_g - V_{th}) \qquad 3b \qquad \text{the saturation region}$$

We used MATLAB software to calculate the I-V characteristics of our model.

Results and Discussion

Horizontal OFET

The design of this device provided a possibility to explore the properties of OFET device in a way that is similar to the corresponding inorganic devices [18]. The basic function of OFETs in the horizontal devices is depending on the direction of charge transport. The present work employed a sample of organic polymer (P3HT as an active layer) of the transistors to study the electrical properties of the horizontal OFET device. This material is presented and described in the following paragraph.

Output Characteristics of P3HT based Horizontal OFET

In this paragraph, we explain the current-voltage characteristics based on the gradual channel approximation for different gate insulators used by a monolayer ZrO_2 and PVA. The output characteristics of the OFET are calculated from equations 1and 2, while selected parameters are used to calculate the output characteristics (the linear and saturation regime (I_d-V_d) characteristics), as shown in Tables-(1 and 2).

Table 1-The parameters employed in the present study [19].

Parameter	Value
length of channel L	$4X10^{-6}$ m
width of channel W	$300X10^{-6}$ m
Mobility μ	0.15 m/V.s
threshold voltage V_{th}	-2.5 Volt
Dielectric thickness	$300X10^{-9}$ m
Semiconductor thickness	$1600X10^{-9}$ m

Table 2-dielectric constant for the dielectric materials and semiconductor employed in this study [20, 21]

Dielectric		Dielectric constant ε
poly(vinyl alcohol)	PVA	7-8
Poly(3-Hexylthiophene)	P3HT	4.4
zirconium dioxide	ZrO_2	25.3

The output characteristics of P3HT are shown in Figures- 2 and 3 based on horizontal OFET as a function of the drain voltage (V_d=-40 to 0V) for values of different gate voltages (V_g= -40, -30,-20,-10

and 0V) by using single layer for different gate insulators (ZrO_2 and PVA). It was observed that the operating regimes of the horizontal OFET device can be divided into two regions; first, the linear region, which starts with increasing drain voltage $V_{d=}0$ V, and ends with drain voltage that reaches the "pinched off " point ($V_d \sim V_g - V_{th} = 17.5$ V). At this voltage, a depletion region is formed, while by the continuous increase of V_d, the second region (saturation region) is formed. Further increase of voltage leads to the formation of a depletion region from the "pinched off" point to the drain electrode area, where the difference between the local potential V(x) and gate voltage is below the threshold voltage. At that time, a space-charge limited saturation current can flow across the depletion region by high electrical field [22]. At the ($V_g - V_{th}$) point and unchanged source, a saturation regime will be formed.

The decrease in the values of current is due to the shift in the threshold voltage by about 2.5 V towards negative voltages. This behavior is typical for p-type horizontal OFETs when the traps are present at P3HT /insulator interface. Linear and saturation regimes indicates a good Ohmic contact for P3HT and the electrodes. Table-3 shows the maximum drain current in the linear and saturation region for both gate insulators at Vg=-40V.

Table 3-maximum values of drain current for both gate insulators at V_g = -40 V.

Materials	Drain Current I_d (A)	
	Linear region	Saturation region
ZrO_2	-1.859×10^{-5}	-1.864×10^{-5}
PVA	-1.740×10^{-5}	1.745×10^{-5}

It can be observed that an improvement occurred in the drain current using ZrO_2 insulator as compared to the PVA insulator. Such behavior can be attributed to the effective capacitance ($C_i = 7.4635 \times 10^{-4}$nF) and the high dialectic constant of ZrO_2,

$$C_i = \varepsilon_\circ \varepsilon /t \tag{4}$$

Where t is the thickness of the dielectric, $\varepsilon_\circ$ is the vacuum permittivity. This result agrees with many previous studies and with the expected results by ITRS (International Technology Roadmap for Semiconductors) when using materials with high dielectric constant [23, 24].
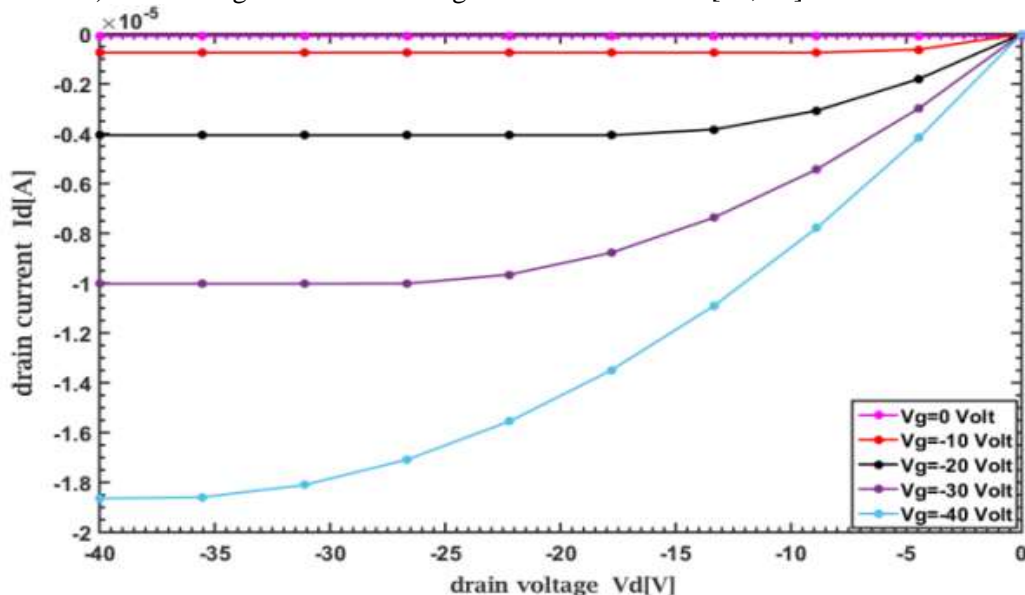

Figure 2-Output characteristics of horizontal OFET for the gate insulator ZrO_2.
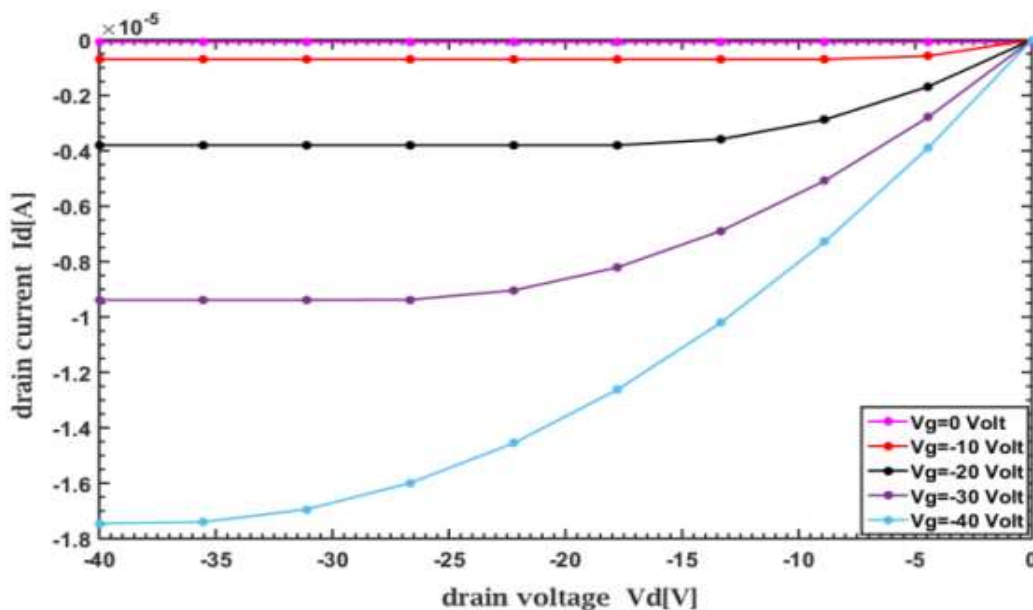
Figure 3-Output characteristics of horizontal OFET for the gate insulator PVA.

Transfer Characteristics of P3HT based Horizontal OFET

In this section, the transfer characteristics of P3HT based Horizontal OFET are studied for different gate insulators (ZrO_2 and PVA) based on the gradual channel approximation model. The results for the p-type channel were obtained by using equations 1, 2, 3a, and 3b. The parameters utilized for these results are presented Tables- 1 and 2. The transfer characteristics in this section include the (I_d-V_g) characteristics and transconductance of the linear and saturation regions for P3HT which illustrated in Figures 4-7. In Figures- 4 and 5, the transfer characteristics (I_d vs.V_g) were represented for different gate insulators (ZrO_2 and PVA) in the linear region for a fixed drain voltage ($V_d = –40V$) and by varying the gate voltage from -40 to 0 Volt. It can observed a significant decrease in the absolute value of the drain current of P3HT horizontal OFET for the high negative gate voltages.

Table-4 show the maximum values of current and transconductance at V_d =-40 V for ZrO_2 and PVA gate insulators. This results show an improvement in the transconductance by using ZrO_2 insulator instead of PVA, and that is because the high dielectric constant for ZrO_2. The present results demonstrate a good agreement with the experiential values [23,25].
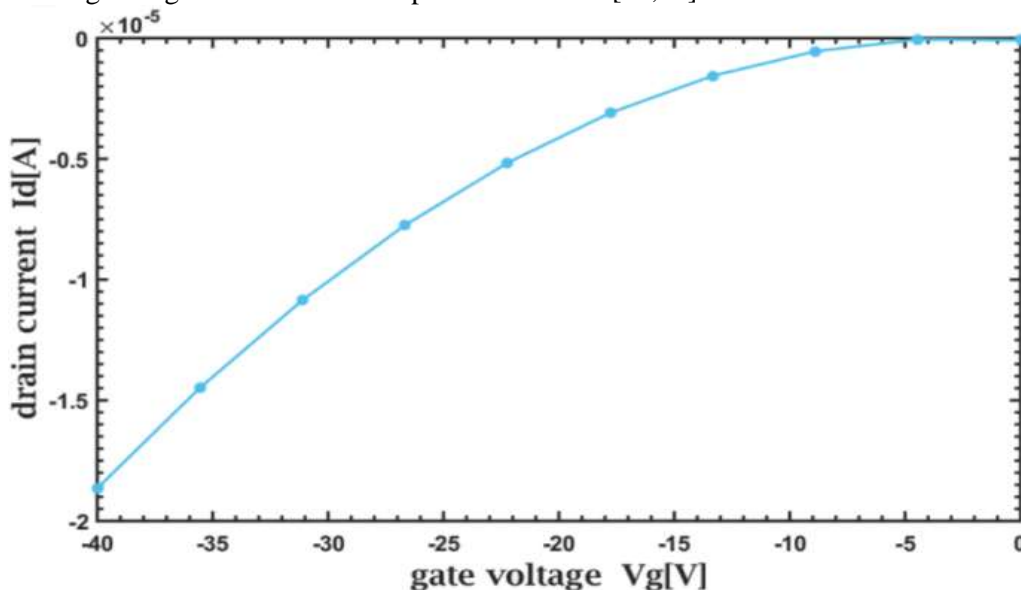

Figure 4-The transfer characterics of horizontal OFET for gate insulator ZrO_2.
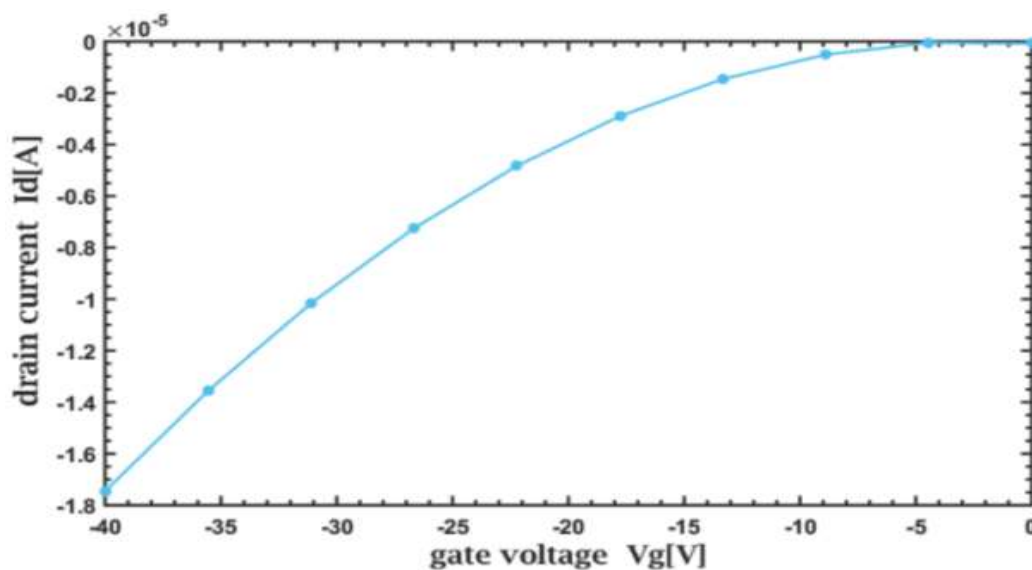
Figure 5-The transfer characteristics of horizontal OFET for gate insulator PVA.

Figures-(6, 7) present the results of transconductance as a function of gate voltage for P3HT horizontal OFET at drain voltage -40V for the used gate insulators. The maximum values of the transconductance are represented in Table- 4. The results also indicate a high transconductance value for ZnO_2 against PVA which agree with [26].
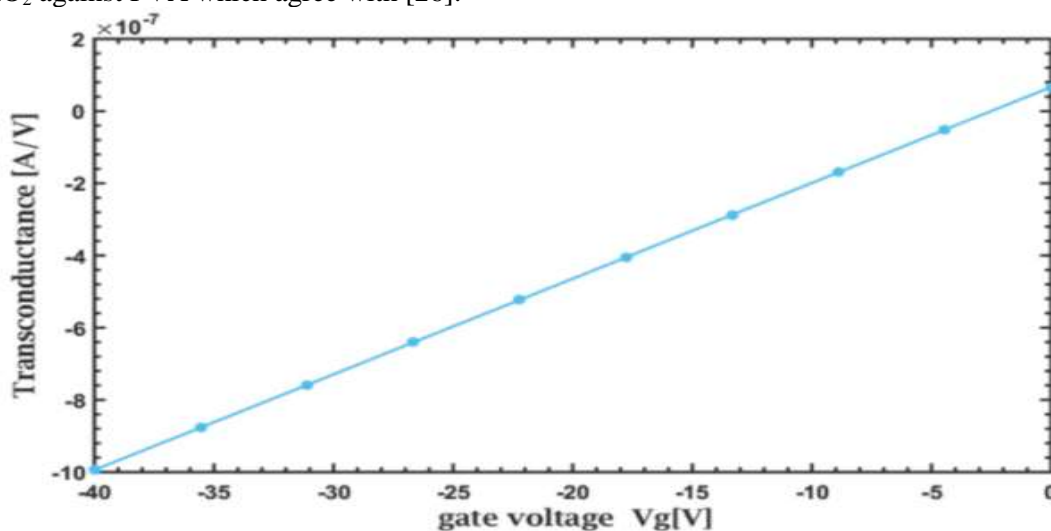

Figure 6-ransconductance of horizontal OFET for gate insulator ZrO_2.
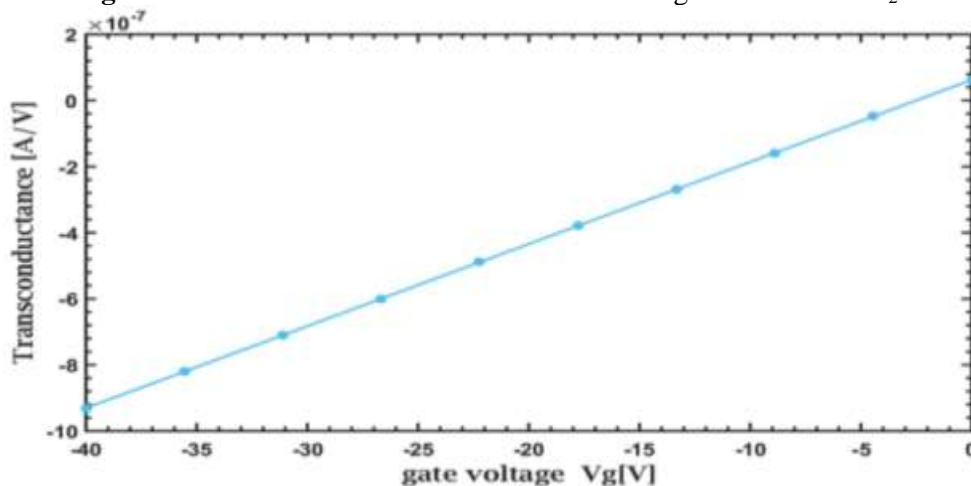

Figure 7-Transconductance of horizontal OFET for gate insulator PVA.

Table 4-maximum values of drain current and transconductance for both gate insulators

Materials	Drain Current I_d (A)		Transconductance g_m (A/V)
	Linear region	Saturation region	
ZrO2	1.856×10^{-5}	1.864×10^{-5}	0.9943×10^{-6}
PVA	1.737×10^{-5}	1.745×10^{-5}	0.9308×10^{-6}

Vertical OFET

In order to overcome the performance restrictions of the horizontal OFETs, the use of VOFETs was introduced. The quantitative analysis of VOTFTs based on the gradual channel approximation. The basic OFETs into vertical devices, depending on the direction of charge transport. The current study used two examples of p-type organic polymers for P3HT as active layer material in this device, where the electrical characteristics of VOFET the device were compared with those of the horizontal OFET device.

Output Characteristics of the P3HT based Vertical OFET

Figures-(8, 9) present the plot of the drain-source current (I_d) versus the drain-source voltage (V_d=-40 to 0 V) for different gate-source voltages (V_g) of the monolayer for the two of P3HT based Vertical OFET. The curve show that the drain current I_d exhibited a saturating trend with increasing drain voltage V_d above V_g also demonstrated that the pinch-off region was properly formed in the vertical channel in the vicinity of the drain electrode (Au). The results are in a good agreement with the experiential values [27, 28].

It can be observed than an improvement of the drain current occurred by using the ZrO$_2$ insulator as compared to PVA. Such behavior can be attributed to the increase of effective capacitance C$_i$.
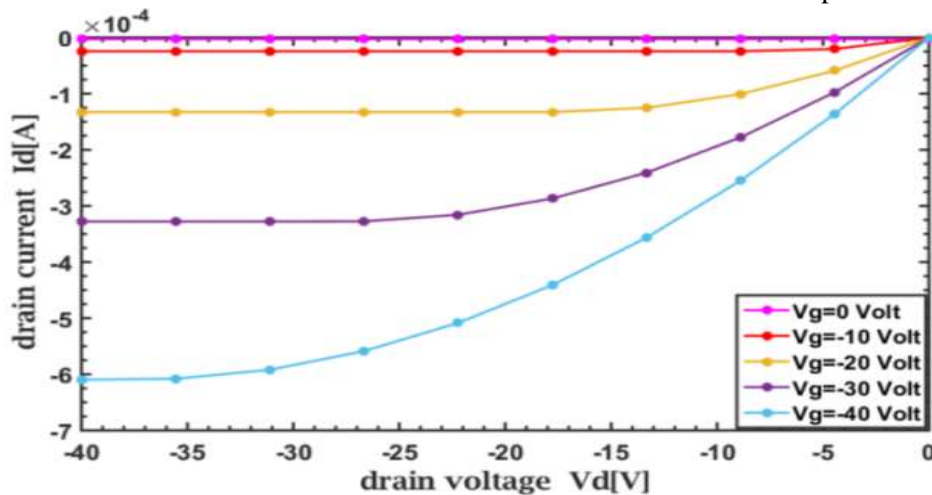

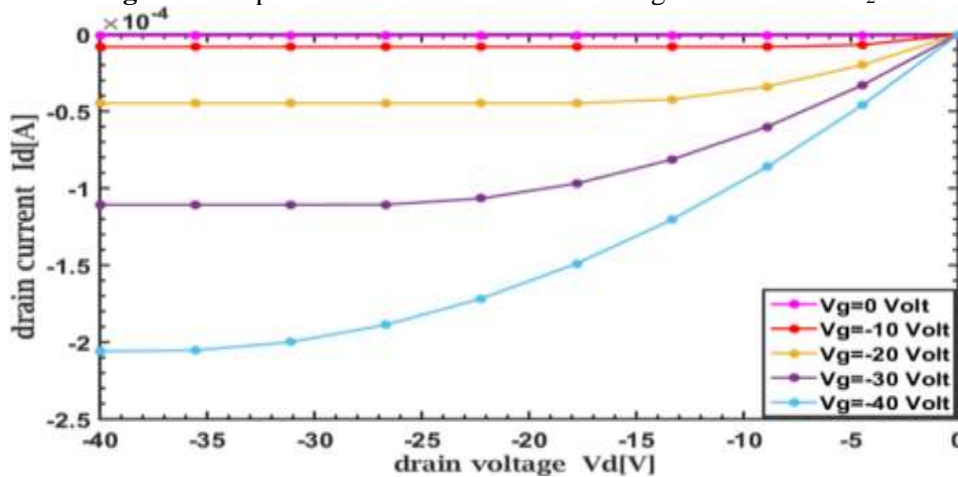**Figure 8-**Output characteristics of VOFET for gate insulator ZrO$_2$.

Figure 9-Output characteristics of VOFET for gate insulator PVA

Table 5-maximum values of drain current for both gate insulators at V_g = -40 V

Materials	Drain Current I_d (A)	
	Linear region	Saturation region
ZrO_2	-6.080 x10^{-4}	-6.096x10^{-4}
PVA	-2.054 x10^{-4}	-2.059 x10^{-4}

Transfer Characteristics of P3HT based Vertical OFET

    To investigate the effects of the dielectric layer of the P3HT based VOFET**, t**he present study used different gate insulators with single layer (ZrO_2 and PVA). The (I_d-V_g) characteristics and transconductance were studied using the gradual channel approximation model, as obtained by equations 1 and 2 and the parameters presented in Tables- 1 and 2. The linear and saturation regime of the field-effect transconductance voltage was extracted from the linear and saturation regime transfer characteristics using equations 3a and 3b, based on the OFETs gradual channel approximation at low drain-to-source voltage. Figures-(12, 13) show the transfer characteristics (I_d-V_g) as a function of gate voltage V_g =-40 to 0V at a constant drain–source voltage V_d =-40 V for P3HT based VOFET. Figures-10 and 11 illustrate that the drain current (I_d) increased when the gate voltage (V_g) became more negative, along with a clear linear regime and a distinct saturation of drain current. From Table-5 the higher values of the linear and saturation drain current that were recorded for ZrO_2 and PVA can be estimated.

This is due to the high dielectric constant of ZrO_2which increases the capacitance. The results also showed a decrease in the drain current with increasing in the V_g, which is related to the threshold voltage shift only. Such results can be attributed to the increase in the effective capacitance (C_i= 7.4635x10^{-4}nF) of the P3HT, as defined in equation (5) [18]:

$$C_{total} = C_{dielectric} + C_{semiconductor} \qquad (5)$$

Where C_{total} is the total capacitance, $C_{dielectric}$ is the dielectric capacitance and $C_{semiconductor}$ is the semiconductor capacitance.
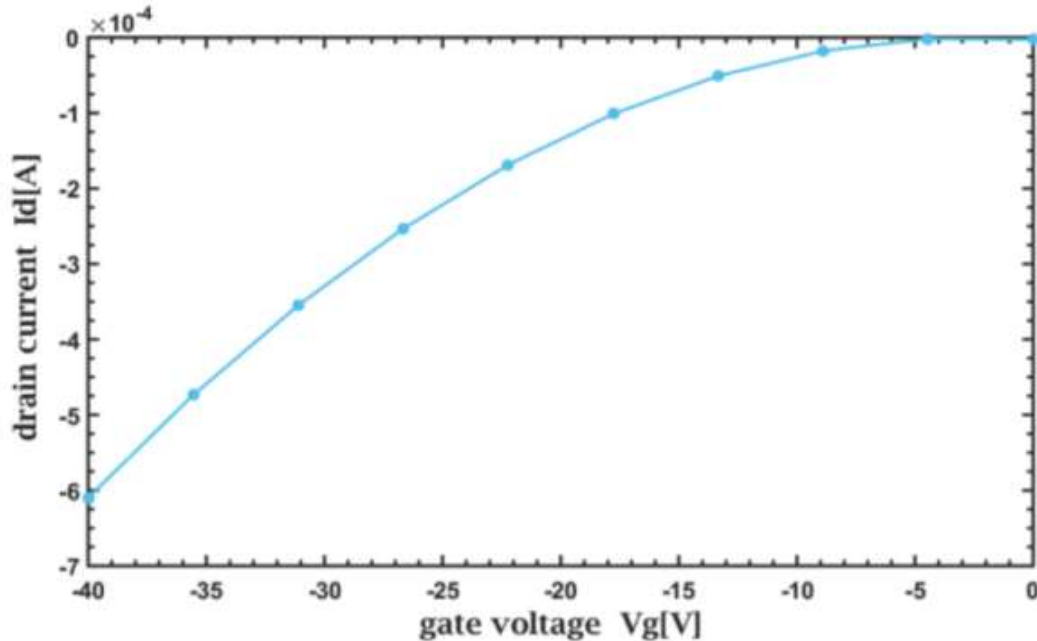

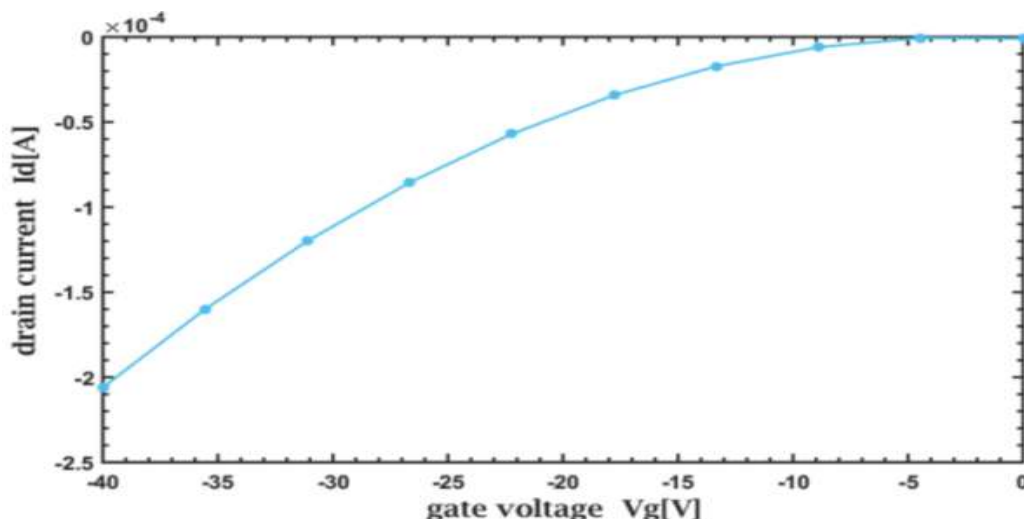**Figure 10-**Transfer characteristics of VOFET for gate insulator ZrO_2

Figure 11-Transfer characteristics of VOFET for gate insulator PVA

Figures-(12, 13) present the transconductance as a function of gate voltage for the P3HT VOFET at a drain voltage of -40V for the two gate insulators. Therefore, an improvement was observed in the transconductance of P3HT by using ZrO_2 insulator as compared to PVA. By comparing the electrical characterization results for horizontal and vertical OFET structure because in VOFET charge transports perpendicular to the plane of substrate, while in the horizontal OFETs devices the charge transports in the same plane of substrate [29].
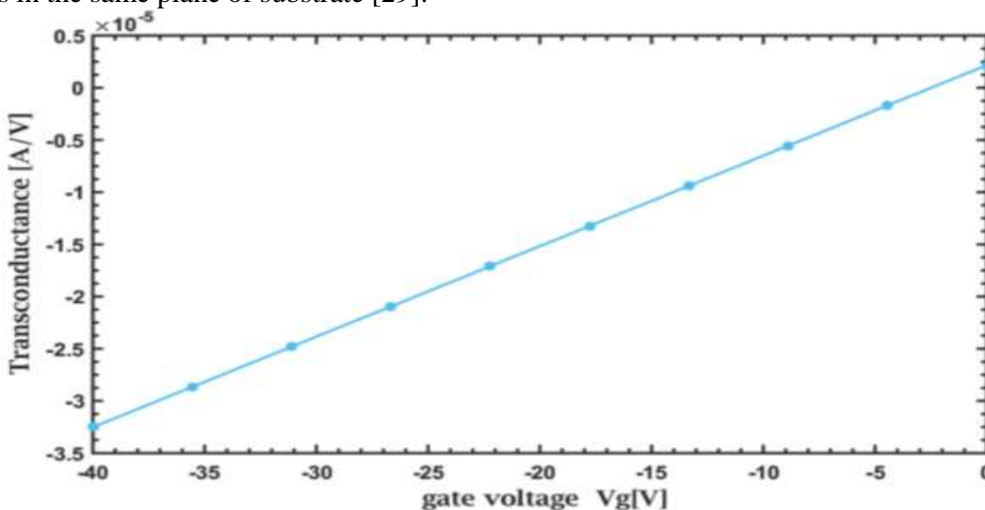

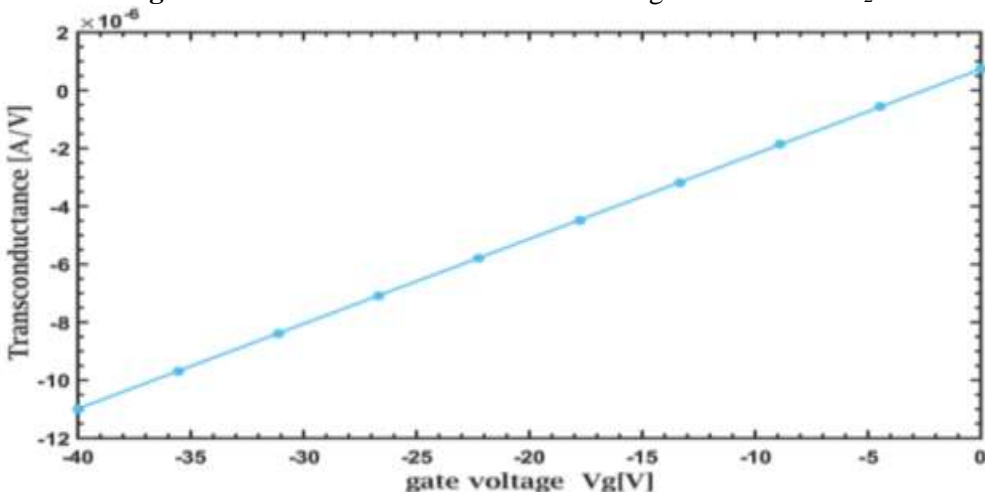**Figure 12-**Transconductance of VOFET for gate insulator ZrO_2

Figure 13-Transconductance of VOFET for gate insulator PVA

Table 5-maximum values of drain current and transconductance for both gate insulators

Materials	Drain Current I_d (A)		Transconductance g_m (A/V)
	Linear region	Saturation region	
ZrO2	-6.069×10^{-4}	-6.096×10^{-4}	-0.3251×10^{-4}
PVA	-2.050×10^{-4}	-2.059×10^{-4}	-0.1098×10^{-4}

Conclusion

Horizontal and vertical OFETs with P3HT as an active layer with ZrO_2 and PVA as an insulating layers were characterized. It is confirmed that the device performance depends on the type of the gate insulator. The best results of output and transfer properties could be obtained for VOFETs. The best results of the electrical properties were observed using the gate insulator ZnO_2 of horizontal and vertical OFETs as compared with those obtained using PVA. Such behavior can be attributed to the effective capacitance.

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