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Enhanced switching ratio and subthreshold swing analysis of different gate dielectric materials effect on OFET performance

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Organic field-effect transistors (OFET) have gained significant interest for their potential in low-cost, large-scale, flexible, and printable electronic devices. However, they face numerous significant challenges, such as high operating voltage and leakage current. This study investigates the impact of using high-dielectric constant materials as gate dielectrics on the performance of OFETs. The goal is to improve OFETs by lowering the operating voltages using high gate dielectric organic and inorganic materials. Aluminum dioxide (Al_2O_3) and polyvinyl alcohol (PVA) were selected as the gate dielectrics due to their favorable properties. MATLAB was used to model and study the electrical characteristics of the device. The device demonstrated typical p-type channel behavior with increasing negative gate bias voltage values. The device shows a clear enhancement using a bilayer of PVA/Al_2O_3 against the monolayer. The results show that the device saturation regime has a high value of on/off ratio (I_{on}/I_{off}), transconductance (g_m), and lower subthreshold swing (SS) of 8.05 x10^2, 4.19x10^{-3} A/V, 1.52. These values indicate that organic materials can potentially produce organic electronic device applications.

Keywords: Pentacene; OFET; Al_2O_3; PVA.

1. INTRODUCTION

Tsumura et al. published the first report in 1987 about organic field effect transistors (OFETs), which have been getting considerable interest in the last thirty years because of their important applications in electronic and optoelectronic devices, chemical sensors, and flexible displays [1–2]. They have become very important in the electronic market because of their many excellent features, including low cost, large-area fabrication, and solution processing [3]. In addition to the gate direction, OFETs can have four other potential structures: alternating bottom gate and bottom contact, top gate and top contact, and bottom gate and top contact. Based on the critical OFET performance criteria of increased discharge and mobility, we found that a bottom gate/top contact was the ideal configuration. [4].

Horowitz [5,6] has demonstrated the basic performance of OFET especially mobility, on-off current ratio model the and charge transport mechanisms in organic semiconductors (OSC). Organic semiconductors, such as small organic molecules and polymers, appear to be the best possible solution for optimizing the performance of OFET. Pentacene, classified as a p-type aromatic hydrocarbon, is regarded as a highly promising organic semiconducting material owing to its remarkable mobility [7]. It is the most extensively studied organic semiconductor material for OFET. OFET based on pentacene material has a typical field effect mobility of around 1 $cm^2/V.sec$ [8]. The main limitations of OFET were the high voltage operations (> 10 V) and the low mobility (<1 cm2 V-1 s-1), which enhance the researchers and scientists to seek a solution that included the selection of high dielectric materials as a useful technique to reduce OFET operating voltage [9,10].

Several recent studies have focused on OFET that employ the inorganic-organic hybrid materials as gate dielectric layers. Photonic devices, light-emitting diodes, thin-film transistors (TFTs), and other thin-film optoelectronic devices can benefit from these materials because of how inexpensive they are [11,12]. Polymer dielectrics, used in see-through transistors and bendable displays, offer several benefits in comparison to inorganic gate dielectrics. B. R. Teja Karri and N. Gupta, 2019 [13] states that they are a useful method for reducing operating voltage and achieving sophisticated flexible electronic applications. The dielectric constant of polyvinyl alcohol (PVA), a polymer that dissolves in water, ranges from 5 to 8. Because they may provide a conducting channel at a few volts without appreciably decreasing the dielectric thickness, inorganic high-k materials (such Al2O3, ZrO2, Ta2O5, HfO2, and TiO2) are frequently employed as dielectric layers. Due to its high band gap energy (7-8 eV), low surface roughness, and high capacitance compared to other polymers, the inorganic dielectric material (Al2O3) has been widely employed as an ultrathin dielectric layer in OFETs. It also functions as an excellent insulator. Nonetheless, Al2O3's dielectric constant (κ) value is comparatively lower than that of other inorganic materials.

Nanotechnology refers to the manipulation and control of matter on a nanometer scale, typically between 1 and 100 nanometers. At this scale, materials often exhibit unique physical, chemical, and biological properties that differ significantly from their bulk counterparts. The scope of nanotechnology is vast, encompassing various fields such as materials science, chemistry, physics, biology, and engineering. It involves the creation and application of materials, devices, and systems through the control of matter at the nanoscale, offering unprecedented opportunities in numerous industries. In this study, the high operation voltage of OFET was considered for testing and finding suitable materials to lower the voltage. PVA and Al_2O_3 are used as the dielectric materials (monolayer and bilayer) for pentacene-OFETs, respectively, and the electrical characteristics of the performance of the devices.

2. THEORETICAL MODELING

2.1 Device Structure

In this work, a top contact/bottom gate (TC/BG) pentacene based OFET transistor was considered, as illustrates in Figure 1. The active material of an OFET employing was pentacene. The construction of the 2D structure by OFET parameters were obtained from an experimental data as illustrated in Table 1.

Silicon was considered a favorable choice for both the base and the gate connections. It was hypothesized that the electrodes of source and drain were composed of gold (Au). The calculation of I_d in the immediate vicinity is performed using the conventional model of field-effect transistors [16]:

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

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

The below equations express the transconductance for the two regions (linear and saturation) of the OFET [17]:

$$g_m = \frac{\partial I_d}{\partial V_g} = \mu C_i \frac{W}{L} V_d \quad (3)$$

$$g_m = \frac{\partial I_D}{\partial V_g} = \mu C_i \frac{W}{L}(V_g - V_T) \quad (4)$$

The variables C_i, V_g, V_d, and μ represent the effective capacitance, gate voltage, source-drain voltage, and mobility respectively. The subthreshold swing (S.S.) and switching raio (I_{on}/I_{off}) where calculated depending on the below equations [18]:

$$SS = 2.3\,\frac{KT}{q}\left(1 + \frac{C_s}{C_i}\right) \quad (5)$$

$$\frac{I_{on}}{I_{off}} = \frac{\mu C_i V_d}{2 t_s \sigma} \quad (6)$$

Table1 Parameter for simulation structure.

Parameter	Value
Channel length (L)	100µm
Channel width (W)	50µm
Pentacene thickness (t_s)	50nm
AL_2O_3thickness (t_{ox})	300nm
PVA thickness (t)	150 nm
Dielectric for pentacene	4.4
Dielectric for PVA	10.4
Dielectric for AL_2O_3	12
Capacitance for AL_2O_3	1.007 nF/cm^2
Mobility	5 cm^2 /v.s
threshold voltage	-2.5 v

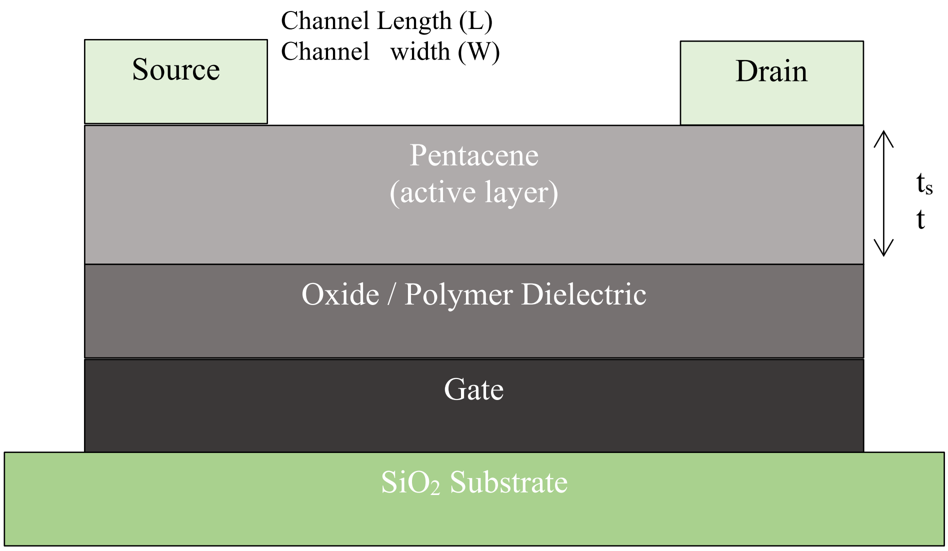

Figure 1 Architecture of OFET.

2.2 Characterization using MATLAB simulation

The EEE1620-2008 Standard for OFETs Characterization was used to the traditional theory of conventional MOSFET transistors to determine key parameters such as mobility, threshold voltage, on-off current ratio, and contact resistance [21]. Equations (1-6) were used to simulate the proposed model, assuming that the field along the channel is significantly lower than across it (gradual channel approximation) and the mobility remains constant; the electrical characterization of pentacene-based OFETs was used to derive parameters was done using MATLAB (2020a) simulation. The terminal characteristics of our model were I_d (V_g, V_d), which is restricted V_d=0 to -5V.

3. RESULTS AND DISCUSSION

In this research we used two materials (PVA/Al_2O_3) to enhance the value of switching ratio and subthreshold swing for OFET and we found the value of Al_2 O_3 is better than PVA and the best result is when they are combined together and made bilayer. The electrical performance of Pentacen based OFET using the two gate dielectrics Al_2O_3 and PVA are investigated. Figure 2 and 3 display the output and transfer characteristics of these devices. Figure 2 shows a linear region at low drain voltage (V_d) indicating the possibility of holes at the pentacence and gate dielectric contact. From source to drain, the value of Vg determines the direction of current flow in a channel.The onset of the saturation region occurs when the drain-to-source voltage (V_d) reaches the threhold voltage(V_T), resulting in V_d being equal to V_g-V_T. Within this specific region, the drain current reaches an amount of saturation due to the reduced electric field, resulting in the narrowing of the channel. In this specific area, the drain current shows no correlation with the drain voltage [31,32]. To achieve saturation, significant negative drain voltages must be applied. Research indicates that OFETs based on pentacene usually function in the accumulation mode. During this mode, the dominant charge carriers are holes, which gather within the conducting channel [33-36].

Figure 2c depicts the observed amplification in the drain current when employing a bilayer dielectric material composed of PVA/Al_2O_3, in comparison to individual layers of Al_2O_3 and PVA. This enhancement therefore leads to an augmentation in the number of charge carriers. Equation (5) [37] demonstrates the increase in the effective capacitance Ci suggests that the bilayer functions as a gate insulator with reduced gate leakage. A high dielectric constant value can enhance the creation of free carriers at the interface between the semiconductor and dielectric. When a voltage (V_g) is applied to the device, these carriers can enter the channel. Thus, a lower voltage can be used to fill the traps close to the interface [38].

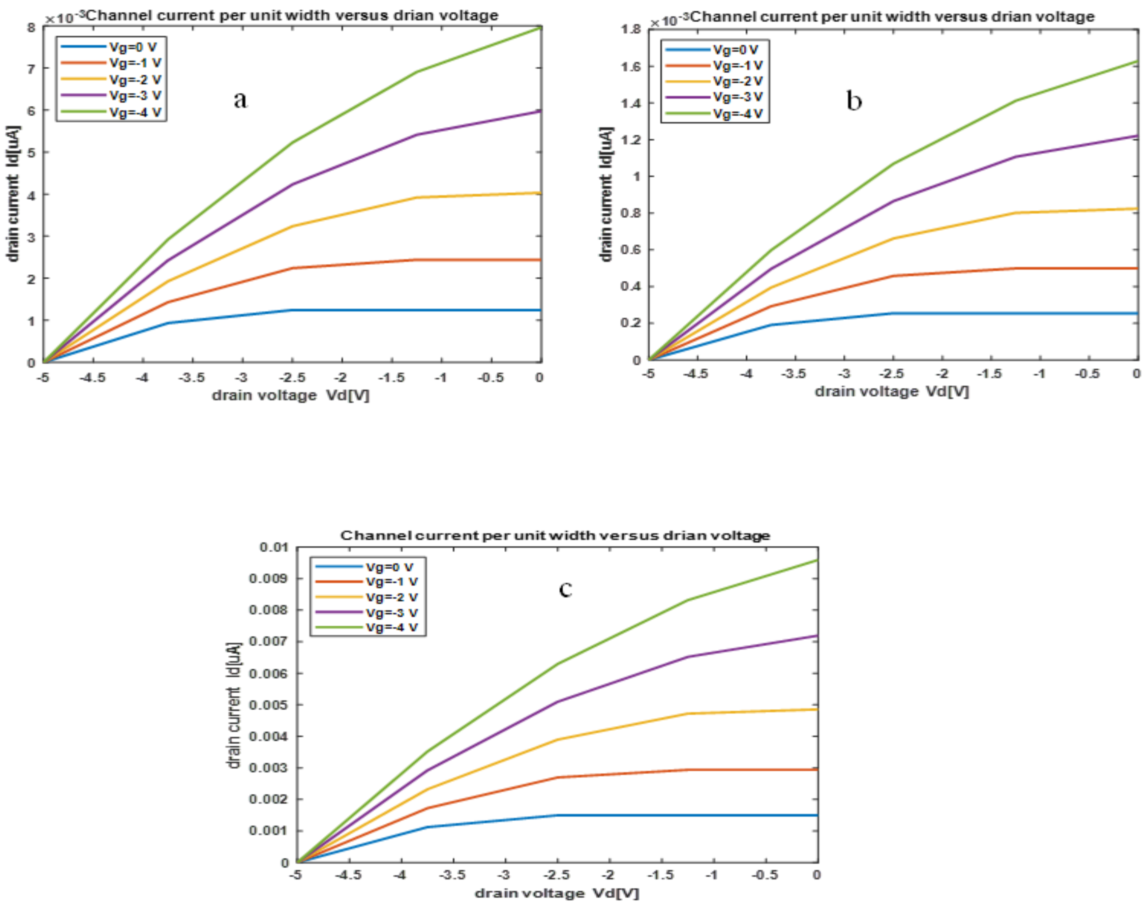

Figure 2 The OFET output characteristic for a-Al_2O_3 b-PVA c-PVA/Al_2O_3 composite.

Figure 3 depicts the variation of the drain voltage, ranging from a minimum of -5 V to a maximum of 0 V. Increasing the drain voltage results in an increased on/off ratio and a lower subthreshold slope value for the device. By raising the drain voltage, the drain current can be increased, depending on the channel of carrier conduction. To calculate the average subthreshold slope, it is necessary to understand the transitions that take place between the on-state and the off-state [39]. From Figure 3, the higher drain current of PVA/Al_2O_3 is caused by the great value capacitance of these gate dielectric materials comparing with the both materials in the pure case. The greater dielectric capacitance can assist in accumulation of additional charge carriers in the conducting channel. An increase in the value of the on-off current ratio signifies successful control of carrier conduction through the channel.

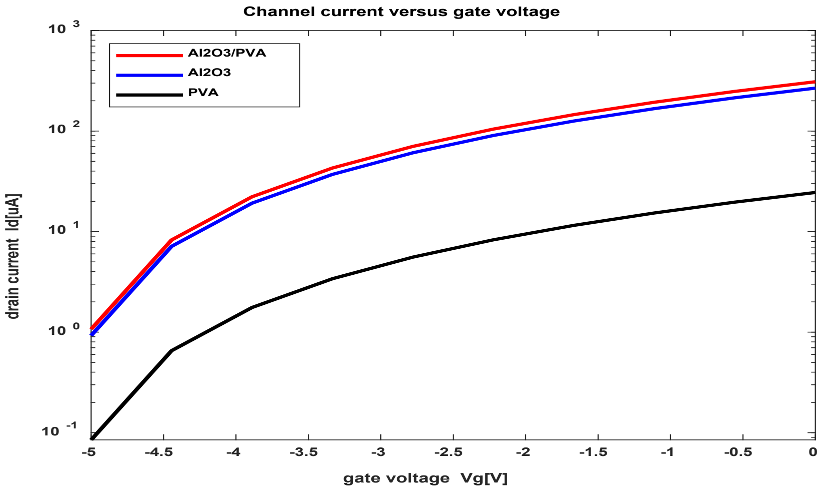

Figure 3 The OFET transfer characteristics for PVA, Al_2O_3, and PVA/ Al_2O_3.

Table 2 The result parameter.

Dielectric k/Materials	I_{on}/I_{off} ratio	SS
PVA	2.07e01	1.38
Al_2O_3	4.28e02	1.51
PVA/ Al_2O_3	8.05e02	1.54

The transconductance (g_m) is an essential performance parameter of transistors. The transconductance of the transistor exhibits a direct proportionality to its frequency. Therefore, a high transconductance results in devices that have rapid switching speeds [39]. Figure 4 exhibits the relationship between transconductance and gate voltage in an OFET, with a fixed drain voltage of -5 V. The transconductance values for the insulators Al_2O_3, PVA, and PVA/Al_2O_3 were determined to be 3.04×10^{-2}, 0.44×10^{-3}, and 4.19×10^{-3} A/V, respectively, when the V_g was set to 0V. The transconductance achieved with Al_2O_3 insulators exceeds that of PVA. Nevertheless, the PVA/Al_2O_3 dielectric material exhibited the highest transconductance value. [40-43].

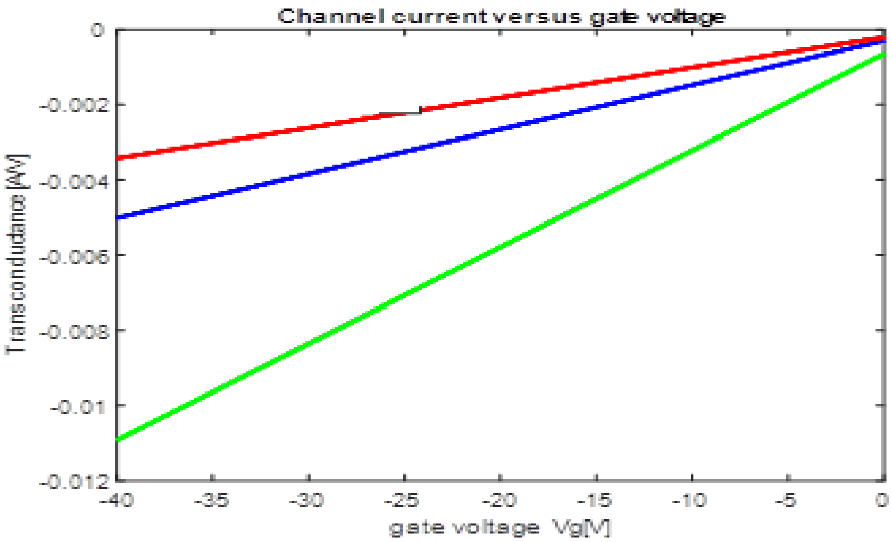

Figure 4 The OFET Transconductance characteristics for PVA, Al_2O_3 and PVA/ Al_2O_3.

4. CONCLUSIONS

The main electrical characteristics of an organic field-effect transistor (OFET) based on p-type pentacene were investigated in this study through the use of simulation analysis in MATLAB software. Two types of gate insulators, PVA and Al2O3, were employed. The PVA/Al2O3 composite gate dielectric exhibited favorable properties in comparison to both pure PVA and Al2O3 gate dielectrics. The PVA/Al2O3 gate dielectric demonstrated the most favorable outcomes for the primary parameters. Specifically, it exhibited an Ion/Ioff ratio of SS and transconductance values of 8.05 x102, 1.54, and 4.19x10-3 A/V, respectively. Finally, we suggest for further investigation to use Tri layer of high dielectric materials to achieve better value for OFET.

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