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Influence of Dielectric and Semiconductor Thickness on Performance Parameters in Organic Field-Effect Transistors

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ABSTRACT: The mobility and current-handling capabilities of Organic Field-Effect Transistors (OFETs) are critical parameters that determine their electrical performance, significantly influenced by material properties and layer thicknesses. In this study, we present a simulation-based analysis of an OFET structure, employing pentacene as the active layer and hafnium dioxide (HfO_2) as the dielectric material. The electrical characteristics of the OFET are investigated by systematically varying the thickness of the dielectric layer (from 5 nm to 7 nm) and the pentacene layer (from 10 nm to 30 nm), while keeping one parameter constant at a time. Key performance metrics such as drain current, transconductance, and charge carrier mobility are analyzed. Our findings reveal that while a thinner dielectric layer enhances capacitance, the transconductance effect has a more pronounced impact on mobility, likely due to changes in the transverse electric field. Additionally, increasing the pentacene layer thickness leads to a reduction in mobility. The highest mobility values obtained are 0.0708 cm^2/Vs for a 7 nm dielectric thickness and 0.0655 cm^2/Vs for a 10 nm pentacene thickness. These results provide valuable insights into the optimization of OFET performance through structural parameter tuning.

KEYWORDS: Organic Field-Effect Transistors (OFET), Bottom gate-top contact, Numerical simulation, Performance parameters.

1. INTRODUCTION

Organic semiconductors have gained significant attention in electronic and optoelectronic devices because of their tunable semiconducting behavior, ease of synthesis and convenient manufacturing processes [1]. Organic semiconductors (OSCs) have significantly lowered production expenses, driving growth in the organic electronics industry. The device is economical because organic transistors may be produced directly and has a low temperature requirement. Many researchers utilized flexible substrates like glass and plastic [2], which led to extremely low production costs. Organic thin film transistors are used in a wide range of advanced applications, including organic light emitting diodes (OLEDs), displays, radio frequency identification tags, sensors [3], and many more.

However, an issue in organic semiconductor is it's mobility, which is much lower than bulk semiconductor. The use of new materials has led to an improvement in OSC mobility. Pentacene, P3AT, P3OT, and P3HT are just a few OSCs that may be used with the manufacturing process [4]. Pentacene OFETs exhibit exceptional electrical performance with high mobility, favorable threshold voltage and excellent switching characteristics [5].

The charge transport dynamics are analyzed in this study by TCAD simulation by separately optimizing the thickness parameters of both the gate dielectric and pentacene active layer to understand their individual contributions.

2. MODELING AND SIMULATION OF DEVICES

The electrodes, which include the gate, drain, and source, the gate dielectric, and the OSC layer are all made up of the OFET. The architecture of an OFET is dictated by the location of the gate dielectric, which may be positioned either upwards or downwards. The layout of these layers typically relies on the device design. As a consequence, we named the source and drain contacts of the organic semiconductor layer top gate (TG) and bottom gate (BG), as well as top and bottom contact structures [6]. Here we considered bottom gate – top contact (BGTC) structure.

The device features an aluminum (Al) gate electrode with a thickness of 20 nm, topped by a hafnium dioxide (HfO_2) dielectric layer (relative permittivity, $\varepsilon_r = 22.0$ [7]). The organic semiconductor (OSC) consists of p-type pentacene with a doping concentration of 3×10^{17} cm^{-3}. Gold (Au) source/drain electrodes (20 nm thick) contact the active pentacene channel. The channel length and width were 10 μm and 220 μm respectively.

To investigate thickness-dependent charge transport, two sets of devices were analyzed:

1. Dielectric thickness variation: HfO_2 layer tuned from 5 nm to 7 nm while maintaining a 30 nm pentacene layer.
2. Semiconductor thickness variation: Pentacene layer adjusted from 10 nm to 30 nm with a fixed 7 nm HfO_2 dielectric.

Here, the visual schematic of the OFET has been shown in the Fig.1.

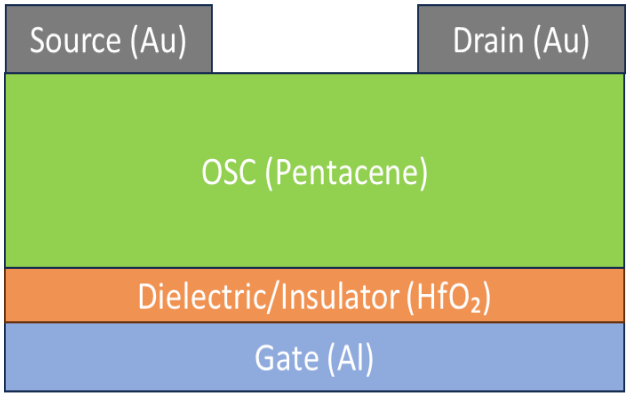

Fig. 1. Schematic view of designed OFET

3. EXTRACTION OF MOBILITY

The IEEE 1620-2008 Standard for Organic Field-Effect Transistor (OFET) characterization recommends adopting conventional MOSFET theory for extracting key device parameters. These include charge carrier mobility, threshold voltage, on/off current ratio, and contact resistance, following established field-effect transistor principles [8]. The common drain current equation can be expressed in linear region as:

$$I_{ds} = \frac{W}{L}\mu C_i \left(V_{gs} - V_t\right)V_{ds} \text{.....(1) [9]}$$

Where,

I_{ds} = Drain current
μ = Field effect mobility
C_i = Capacitance per unit area of gate insulator
W = Channel width
V_{gs} = Applied gate to source voltage
V_{ds} = Applied drain to source voltage
V_t = Threshold voltage
L = Channel length

To extract the mobility, we require the transconductance (g_m). The transconductance (g_m) is determined by calculating the derivative of the drain current (I_{ds}) with respect to the gate voltage (V_{gs}) from the transfer characteristics [9]. So, the transconductance is:

$$g_m = \frac{\partial I_{ds}}{\partial V_{gs}} = \frac{W}{L}\mu C_i V_{ds} \text{ .....(2)}$$

From here, we find the mobility:

$$\mu = \frac{L g_m}{W C_i V_{ds}} \text{ .....(3)}$$

4. RESULTS AND DISCUSSIONS

i. Initial Simulation Study:

The device structure was first simulated with systematic variation of the gate dielectric thickness (HfO_2) from 5 nm to 7 nm in 1 nm increments, while maintaining a constant 30 nm pentacene organic semiconductor layer. For each dielectric thickness configuration, the current-voltage characteristics (I_{ds} - V_{gs}) were simulated and analyzed. Charge carrier mobility values were subsequently calculated using Equations (2) and (3). The I_{ds}-V_{gs} curve of different dielectric thickness layer has been plotted in Fig.2.

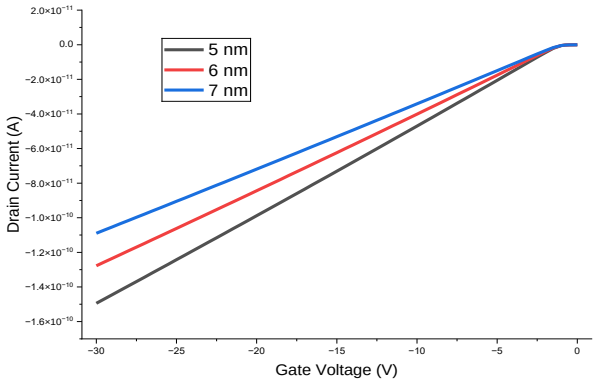

Fig. 2. I_{ds}-V_{gs} graph of different dielectric thickness

The charge carrier mobility in linear region of OFET of different dielectric thickness has been plotted in Fig.3.

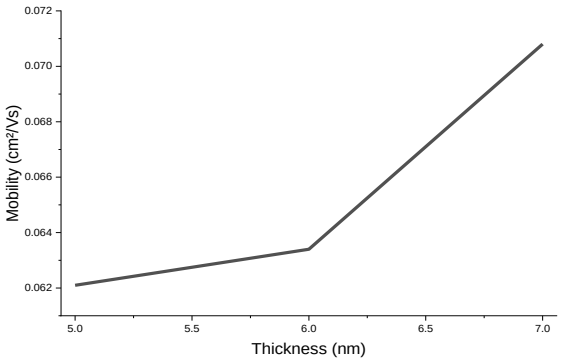

Fig. 3. Mobility for different dielectric thickness

The charge carrier mobility demonstrated a clear positive correlation with dielectric thickness, increasing from 0.0621 cm²/Vs to 0.0708 cm²/Vs as the HfO_2 layer was thickened from 5 nm to 7 nm. Specifically, we observed:

- 5 nm HfO_2: μ = 0.0621 cm²/Vs
- 6 nm HfO_2: μ = 0.0634 cm²/Vs
- 7 nm HfO_2: μ = 0.0708 cm²/Vs

This 14.2% enhancement in mobility suggests improved charge transport efficiency with thicker dielectric layers, likely due to reduced interface scattering effects.

ii. Subsequent Simulation Study:

Building upon these results, a second set of simulations was performed where the pentacene layer thickness was varied from 10 nm to 30 nm in 10 nm increments, while keeping the HfO_2 dielectric layer thickness constant at 7 nm. This complementary approach allowed for independent investigation of semiconductor thickness effects on device performance. Corresponding I_{ds} - V_{gs} characteristics were generated for each pentacene thickness configuration, with mobility values again extracted using the same analytical

expressions. The I_{ds} - V_{gs} curve of different pentacene thickness layer has been plotted in Fig.4.

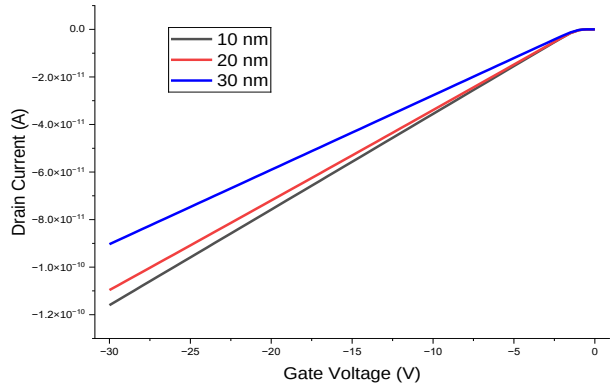

Fig. 4. I_{ds}-V_{gs} graph of different pentacene thickness

The charge carrier mobility in linear region of OFET of different pentacene thickness has been plotted in Fig.5.

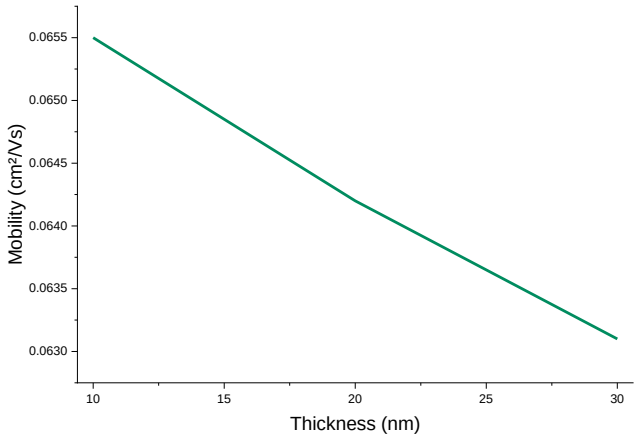

Fig. 5. Mobility for different pentacene thickness

Increasing the organic semiconductor thickness resulted in a gradual mobility degradation:

- 10 nm pentacene: μ = 0.0655 cm²/Vs
- 20 nm pentacene: μ = 0.0642 cm²/Vs
- 30 nm pentacene: μ = 0.0631 cm²/Vs

The 3.7% reduction in mobility across this thickness range indicates that charge transport in pentacene is most efficient in thinner active layers, possibly due to better gate field control and reduced bulk trapping effects.

5. CONCLUSION

This simulation study systematically investigated the impact of layer thickness on the performance of pentacene-based OFETs by independently varying the HfO_2 dielectric thickness (5–7 nm) and pentacene semiconductor thickness (10–30 nm). The opposing trends observed for dielectric versus semiconductor thickness variations provide important insights for device optimization, suggesting that balanced thickness engineering of both layers is crucial for achieving peak OFET performance. The maximum mobility of 0.0708 cm²/Vs was obtained with the 7 nm HfO_2/30 nm pentacene configuration, while the 7 nm HfO_2/10 nm pentacene combination yielded the most favorable results (0.0655 cm²/Vs) among the semiconductor thickness variations. The real-world testing under diverse climatic conditions will provide more comprehensive insights into system performance.

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