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Channel Length Modulation in a Polystyrene Insulated Organic Field Effect Transistor Using PEDOT: PSS Composite Electrode

Ahmet DEMİR*1

ABSTRACT

Channel length-modulated Organic Field Effect Transistor (OFET) was fabricated on a prepatterned source-drain Indium Tin Oxide (ITO) substrate by spin coating method using a Poly (3-hexylthiophene-2,5-diyl) (P3HT) semiconductor and Polystyrene (PS) insulator. Poly (3,4-ethylenedioxythiophene)-poly (styrenesulfonate) (PEDOT:PSS) was used as the gate electrode. Thus, the structure of the OFET device was obtained as ITO/P3HT/PS/PEDOT:PSS. ITO/PS/PEDOT:PSS structure was prepared using the same method for measuring the capacitance of the polymer insulator. Output and transfer current-voltage (*I-V*) characteristics of the electrical characterization of the obtained OFET devices were obtained in full darkness and in the air environment. Basic parameters of OFET devices; voltage threshold (V_{Th}), field effect mobility (μ_{FET}) and the current on/off ratio ($I_{on/off}$) are exracted from the capacitance-frequency (*C-f*) graph of the ITO/PS/PEDOT:PSS structure. Produced PS-OFETs have been found to exhibit good device performance, such as low V_{Th}, acceptable mobility and $I_{on/off}$ values.

Keywords: Polymer gate electrode, Transparent OFETs, Insulators, PEDOT:PSS, Polystyrene, P3HT

1. INTRODUCTION

Organic field effect transistors (OFETs) have received great interest due to their potential to implement low-cost, flexible and wide-area thin-film devices for the fabrication of next-generation universal electronic systems [1-4]. Recently, research efforts have been increased to develop transparent OFETs that are one of the driver components of the pixel multiplier for transparent active matrix displays. In this context, transparent organic field effect transistors (OFET) have received increasing attention as an important building block in transparent electronic systems, and their outstanding properties and the extent of application of modern electrons are expected to expand greatly [5-7]. Transparency, which is needed for some of these applications and brings additional quality and value, is a feature that leads to new possibilities in device design [8]. In this way, numerous transparent conductive films such as indium tin oxide (ITO), carbon nanotube, graphene for transparent OFETs [9-11]. However, the OFETs produced in this way have low work function, high substrate temperature, low permeability and high plate resistance; resulting in increased contact resistance, irregular organic semiconductor film and reduced device permeability [12-15].

The first studies have shown that organic semiconductors are not the only component to produce high quality OFET. At the same time a suitable gate insulator is required as well. OFET gate insulators should meet the standard demands

* Ahmet DEMİR
[1]Department of Physics, Faculty of Sciences, Düzce University, 81620, Düzce, Turkey, ahmetdemir@duzce.edu.tr

of organic electrons in the context of low cost production of organic circuits.

It has been shown that the OFET gate insulators must ideally conform to the flexible surfaces during the coating and be insoluble in the solvent used for organic semiconductors [16-22]. Polystyrene, which is a kind of gate insulator, has good dielectric properties [23]. Polystyrene (PS) is a versatile polymer in terms of chemical and structural properties and can be easily synthesized by various polymerization mechanisms with various orientations and chain lengths [24]. High reactive Polystyrene has become the most frequently used raw material polymer in packaging, insulation and filtration applications for the production of chemically diverse materials including high resistivity and low dielectric loss transparent, solid materials [25]. Thus, PSs as dielectric materials have interesting applications in areas such as electronics and composite materials [26, 27]. PS is a non-polar organic polymer and can be expected to form low energy interfaces with other non-polar materials.

As an alternative to inorganic contacts, the PEDOT:PSS conductive polymer blend has previously been used in solid electrolyte capacitors, organic electronic devices (OECs), and touch screens [28]. PEDOT:PSS, in particular, is a superior material whose conductivity can be adjusted and very good in terms of transparency and film-forming properties [29]. At the same time, PEDOT:PSS is transparent, such as indium tin oxide (ITO), a transparent conductor that is often used in organic electronic devices, and has a higher mechanical flexibility [30].

In this study, it is aimed to fabricate an OFET device using Polystyrene organic dielectric material. The focus of this study is to minimize the interface conditions between the gate insulator and the gate electrode. In this context, first, an organic top gate bottom contact field-effect transistor (TGBC) was fabricated using a transparent electrode PEDOT:PSS with high conductivity as a gate electrode on the prepatterned OFET substrate and this transistor was electrically characterized. It has also been shown that an amorphous Polystyrene polymer that changes the transfer characteristic of OFET devices can be manipulated in the transistor performance. In the study, it has been verified that this OFET device with polymer gate electrode exhibits good current saturation regime and acceptable mobility.

2. EXPERIMENTAL PROCEDURE

2.1. The Preparation of PEDOT:PSS Composite Formulation

PEDOT:PSS PH 1000 and PEDOT:PSS CPP 105D Conductor formulations were procured from Heraus Clevios. Dimethyl Sulfoxide (DMSO) was added to the PH-1000 solution (1:19 by volume) and mixed in the hot plate overnight at 300 rpm at room temperature to provide conductivity enhancement. The resulting mixture CPP-PEDOT was added to control the surface wettability (1:1 by volume) and the resulting mixture was prepared. As a result, a conductive PEDOT:PSS composite formulation was obtained.

2.2. Fabrication of OFET Devices with Polystyrene Polymer Insulator

In this experimental study, prepatterned ITO substrates for OFETs were used as source-drain contacts and PEDOT:PSS composite formulation has been used as gate contact to obtain Polystyrene polymer insulated OFET devices. Prior to the fabrication process, the prepatterned subtrates were dipped in acetone and ethanol, respectively, with 15 minutes sonic shaking. Then all the surfaces have been washed with 2-propanol and dried with a nitrogen gun. P3HT dissolved in chlorobenzene at 8 mg/mL in an unconjugated environment was purchased from Sigma-Aldrich Chemical Company and plated on prepatterned subtrate by spin casting at 3000 rotation per minutes during 60 second. Annealing was carried out by placing the substrate on a hot plate for 60 seconds at 150°C, then taking it from the plate and slowly cooling it at room temperature. As an insulator layer, 15 mg PS polymer was dissolved in 1 mL dichloromethane and coated on the active layer at 1500 rpm for 60 seconds. This film was also placed on a hot plate and heated at 150° C for 60 seconds. All tempering operations were carried out to remove solvents from the films. Finally, the PEDOT:PSS composite formulation was coated on the insulating layer as a gate electrode, at 1000 rpm for 30 seconds. With this last step, the production of PS-OFET devices has been completed. As a result, PS-OFET devices designed as in Fig. 1 have been manufactured.

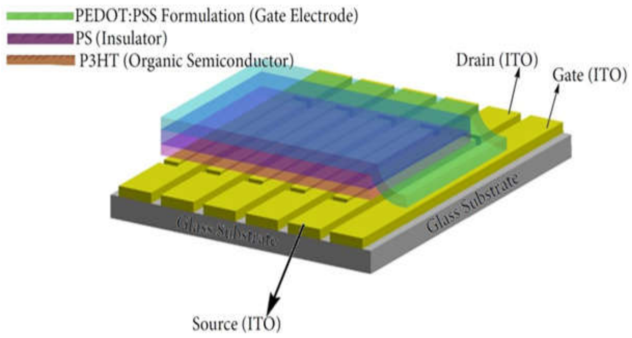


Figure 1. OFET's ITO/PS/PEDOT:PSS based schematic structure.

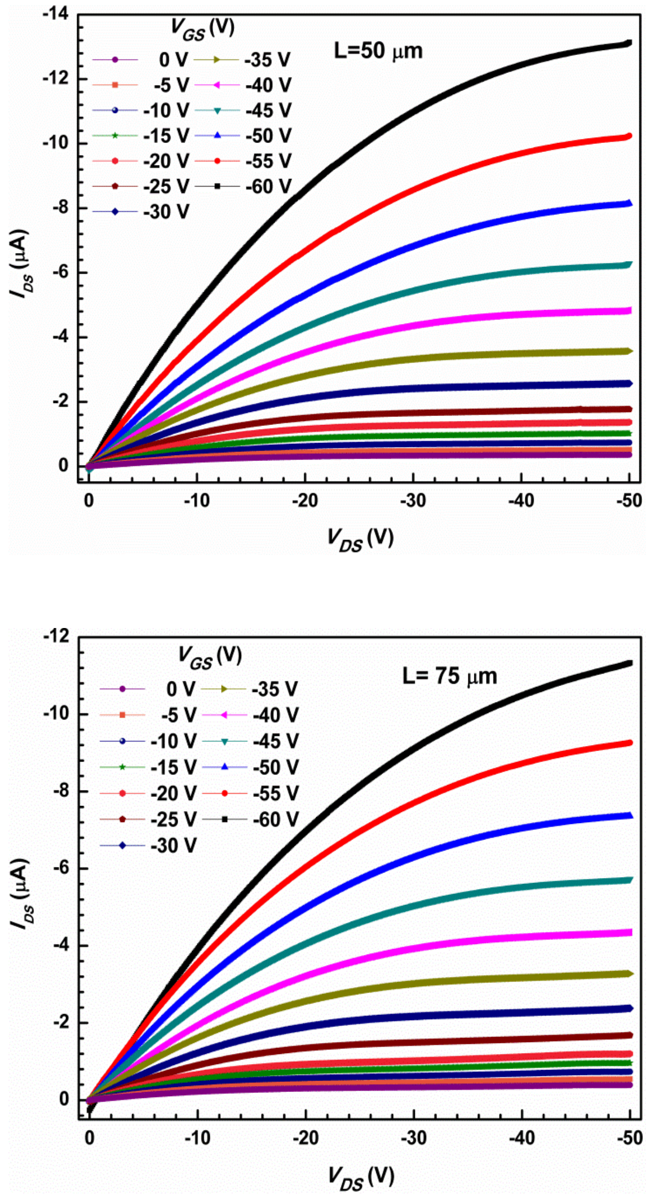
2.3. The Electrical Characterization of TGBC PS-OFET devices

The OFET devices made with PEDOT:PSS composite formulation were placed in a vacuum environment to move away DMSO from the mixture. After the vacuum process, the OFET devices are ready for measurement. Electrical output (*I-V*) measurements of the obtained PS-OFET devices were examined using an OFET test card using a Keithley 2612B SMU device and measurements progressed with 5 V steps gate-source voltage (V_{GS}) between 0 to -60 V and the source-drain voltage (V_{DS}) scan is performed to calculate the gate-source voltage (V_{GS}) and at least 100 data between 0 and -50 V. Besides that the *C-f* measurement for the ITO/PS/PEDOT:PSS structure was performed with the Nova-control Alpha-A Impedance Analyzer Instrument. All characteristic measurement operations are carried out in the dark at room temperature

3. RESULT AND DISCUSSION

The output characteristics of the PS-OFET devices were measured at room temperature and the results are given in Figure 2.The results show that the PS gate insulator exhibits a remarkable output characteristic at -50 V value. The reason for this is that the PS polymer in the gate insulator can increase the flat-lying orientation density of the molecules responsible for enhancing hole mobility [31,32].

A higher channel length may cause lower channel conductivity due to trapped loads. For this reason, the maximum level of current between the source and the drain decreased as the channel length increased [33]. The performance parameters of the OFETs can be modulated by changing the channel length [33,34]. For compatibility between the gate insulator and the composite polymer gate electrode, the charge transfer in the PEDOT:PSS/PS interface was optimized [31,35]. The channel lengths between the contacts were changed between 50 μm to 100 μm.



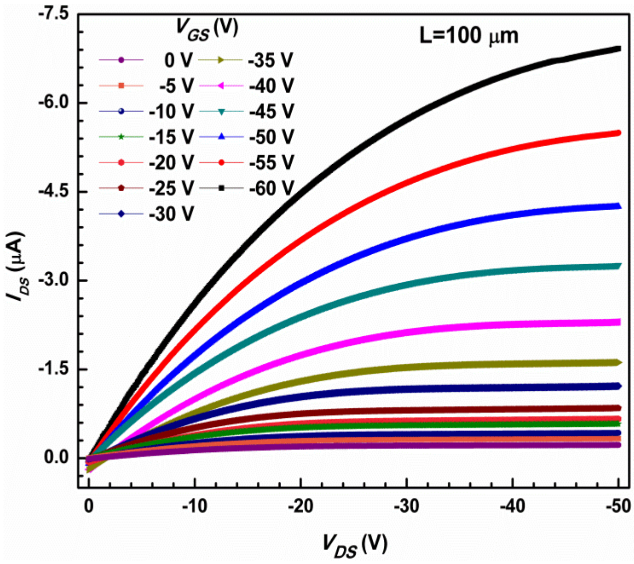


Figure 2. Variation of output characteristics of PS-OFET device according to channel length.

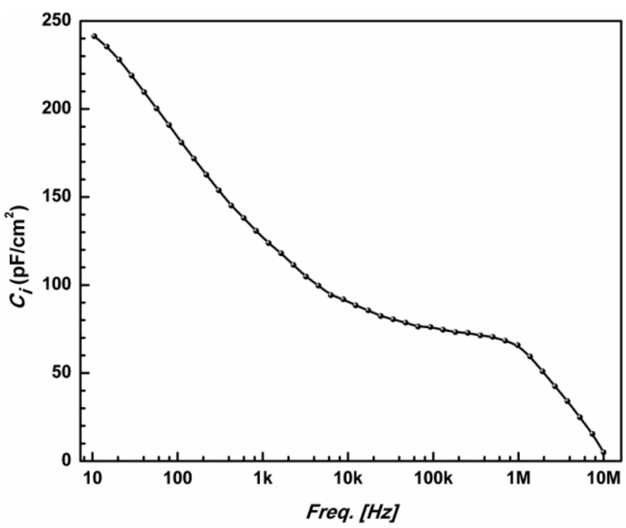


Figure 3. Graph of the effective capacitance of the PS gate insulator according to frequency

The capacitance of the PS gate insulator was obtained from 10 Hz to 10 MHz to calculate the mobility of the devices. The effect of the frequency on the capacitance of the PS gate insulator is exhibited in Figure 3. As obviously seen, the capacity per unit area of the PS gate dielectric is measured to be 220 pF/cm^2. Transistor can operate at high efficiency and shows good performance in terms of high $I_{on/off}$ device [36-39]. Field effect mobility (μ_{FET}) of the OFET can be calculated using the following equation (1) [39-41].

Maximum drain current (I_{DS}) is obtained following formula:

$$I_{DS} = \left[\mu_{FET}\left(\frac{WC_i}{2L}\right)\right](V_{GS} - V_{Th})^2 \qquad (1)$$

Here, W, L, and Ci denote the channel width, the channel length, and the effective capacitance of the insulating layer, respectively.

The semi-logarithmic plot of I_{DS} and V_{GS} at V_{DS} = -50 V for PS gate insulated OFET devices with different channel lengths is shown in Figure 4. It is believed that the reduction in the on/off ratio is due to the channel length effect. As a result, it can be said that in the presence of morphological disorders, the dependence of the $I_{on/off}$ ratio of PS insulated OFET devices on the channel length decreases. These disorders are caused by traps increased with channel width, impurity concentrations, and interface state density.

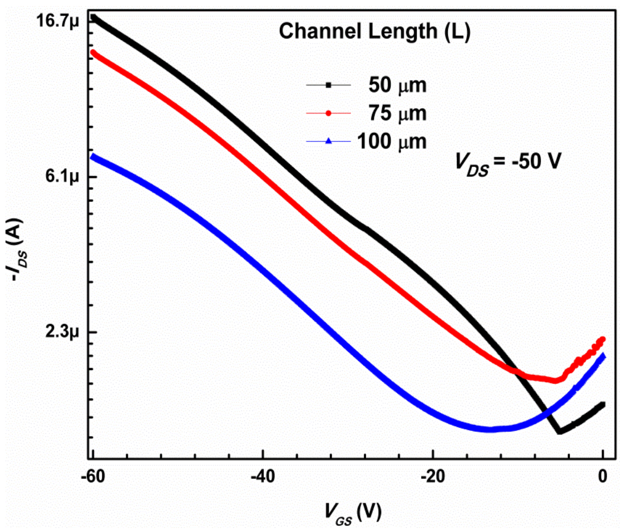


Figure 4. The drain current change of the OFET devices with PS-EDOT gate dielectrics according to the channel length modulation (Semi-logarithmic I_{DS}-V_{GS})

For devices manufactured with PS gate insulation of various channel lengths, $(I_{DS})^{1/2}$ graphs versus V_{GS} at V_{DS} = -50 V can be seen in Figure 5. The main parameters of PS-OFETs at different channel lengths were obtained using graphical data of the $(I_{DS})^{1/2}$-V_{GS} transfer characteristic in the saturation regime. For each channel, the threshold voltages (V_{Th}) of the PS gate dielectrical OFETs can be obtained by the point at which the x-axis of the graph's best linear slope is cut (Figure 5). Mobility is calculated in the linear regime of the drawn transfer characteristics in the saturation regime of the output characteristics (Figure 5).

Field effect mobility can be obtained from the formula below.

$$\alpha = \left(\frac{WC_i}{2L}\right)^{1/2} \qquad (2)$$

Here, α is the best linear slope in Figure 5.

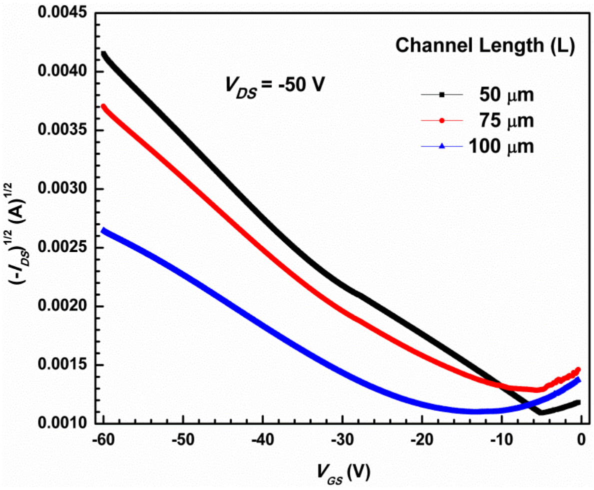


Figure 5. The variation on channel length of the $(I_{DS})^{1/2}$-V_{GS} transfer curves of PS-EDOT gate dielectric-based OFET devices.

3.1. Figures and Tables

The ratio of the $I_{on/off}$ current, which is the ratio of the maximum I_{DS} value to the minimum I_{DS} value, is obtained from the transfer characteristics for each channel length.

Table 1. Performance parameters of the fabricated OFETs.

Channel Length (L)	Threshold Voltage (V_{Th})	Mobility (μ_{FET})	$I_{on/off}$
50 μm	0.38 V	0.569 $cm^2/V.s$	$1.21x10^1$
75 μm	0.8 V	0.487 $cm^2/V.s$	$0.63x10^1$
100μm	1.19 V	0.381 $cm^2/V.s$	$0.36x10^1$

It has been determined that the parameters of "on state and off state of device current ratio ($I_{on/off}$) threshold voltages (V_{Th}) and field effect mobility (μ_{FET}) of PS-OFET exhibiting proportional dependence are dependent on the channel length, and in the on state (accumulation layer formed) it is obtained from I_{DS}-V_{GS} characteristic ($V_{DS} = -50$ V) and given in Table 1. As can be clearly seen from Table 1, as the channel length increases, the Ion/off values decreased as the number of electrical charges trapped between the source-drain electrodes and the other impurities of the PS at the PS/PEDOT:PSS interface increased.

The mobility and threshold voltage values due to the channel length of the PEDOT:PSS formulated gate electrode PS-OFET can be obtained from the equation. As channel length increases, it is clear that field effect mobility (μ_{FET}) decreases from 0.569 to 0.381 $cm^2/V.s$. Similarly, the threshold voltage (V_{Th}) increased from 0.38 to 1.19 V. The change in these two parameters revealed the presence of ionic impurities in the channel between the source and the drain and the charges that were caught in the traps [41]. If simple electrostatic laws are considered, it can be said that the carriers in the longer channel are more localized at the interface due to the larger attractive electrostatic force. In Figure 5, it can be seen that this thinking is correct when considering transfer curves that are exponentially consistent with field effect charges.

CONCLUSION

In this study, produced PS-OFET devices exhibited remarkably good characteristics due to the fact that the PS polymer of the gate insulator can increase the density of flat-lying molecules between the PEDOT:PSS composite electrode and the PS polymer gate insulator. The results obtained are very promising in terms of the $I_{on/off}$, μ_{FET} and V_{Th} values of PS-OFETs. The $I_{on/off}$ values of PS-OFETs vary from $1.21x10^1$ to $0.36x10^1$ depending on the channel length, while the μ_{FET} values range from 0.569 to 0.381 $cm^2/V.s$ with decreasing channel length. These characteristic behaviors may be due to the molecular compatibility and dipole interaction of PS. For this reason, it can be said that PS-OFETs with high conductive polymer composite electrodes show a good interaction between the gate insulator and the gate electrode. In addition, these devices have shown promising performance improvement in some parameters, such as field-effective mobility, threshold voltage, current on/off ratio, and significant response to channel length variations. This study aims to clarify the properties of transparent polymer composite electrode OFETs and to demonstrate the potential use of functional Polystyrene polymer in OFET. From the results obtained so far, further studies on this new study are thought to provide additional opportunities.

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