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The Electrical Properties of Fabricated Pentacene Based Phototransistor with Polystyrene Gate Insulator

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Abstract
In this study, the fabrication of top contact pentacene based phototransistor having polystyrene gate dielectric has been carried out. To analyze the surface morphology of polystyrene insulator and pentacene active layer, scanning electron microscopy (SEM) has been used. The electrical characterization of pentacene based phototransistor and also the effect of illumination on the output characteristics have been investigated. The obtained mobility value and on/off ratio of the transistor are 5×10^{-3} cm^2/Vs and ~10^2, respectively. The increase of the drain current with increasing illumination intensity indicates that the light acts as an additional terminal. Also, this fabricated device behaves as a phototransistor because of its reaction to the illumination.

Keywords: Pentacene, polystyrene, phototransistor.

Polistren Kapı Yalıtkanı ile Pentasen Fototransistör İmalatı

Öz
Bu çalışmada, polistren kapı dielektrikli üst kontak pentasen tabanlı fototransistör imalatı yapılmıştır. Polistren yalıtkanının ve pentasen aktif tabakanın yüzey morfolojisini analiz etmek için, taramalı elektron mikroskobu (SEM) kullanılmıştır. Pentasen bazlı fototransistörlerin elektriksel karakterizasyonu ve aydınlatmanın çıkış karakteristikleri üzerindeki etkisi araştırılmıştır. Transistörden elde edilen mobilite değeri ve on/off oranı sırasıyla 5×10^{-3} cm^2/V ve ~ 10^2'dir. Akaç akımının artan aydınlatma yoğunluğuyla birlikte artması, ışığın ek bir terminal olarak görev yaptığını gösterir. Ayrıca, imal edilmiş bu transistör, aydınlatmaya tepki vermesi nedeniyle bir fototransistör olarak görev görür.

Anahtar kelimeler: Pentasen, polistren, fototransistör.

1. Introduction

The using of small molecules or conjugated polymers organic semiconductors in organic field transistors (OFETs) is comprehensively investigated due to their excellent features such as lightweight, low cost and commercial availability. So far, there have been a number of reports on organic semiconductors using various devices such as electronic paper, radio frequency identification tag, image sensor, flexible display [1-3]. The small-molecule polycyclic aromatic pentacene organic semiconductor material has indicated a great mobility of over 1.0 cm^2/Vs. Pentacene may be an alternative active layer for substitution of amorphous silicon for thin-film transistors applications owing to its unique properties [4-6]. Pentacene active layer can be deposited by thermal evaporation or vapor deposition methods because of its small-molecule structure. The mobility of OFETs has been constantly improved. However, the performance of OFETs is still lower than that of conventional inorganic based transistors. Each component of the transistor should be optimized to enhance the performance of the OFETs. Therefore, numerous studies have been necessitated to overcome some problems such as charge-injection problems, the interaction between inorganic insulator-organic semiconductors, leakage current and

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contact resistance to fabricate transistors with superior performance [7-9]. In order to obtain high efficiency from the OFETs, the choice of the insulating layer is as important as the selection of the active layer. Many dielectrics with various deposition techniques have been operated to prepare gate insulators for OFETs such as magnetron reactive sputtered tantalum pentoxide [10], plasma-enhanced chemical vapor deposition silicon nitride [11], thermal atomic layer deposited silicon dioxide [12]. OFETs are desired to be cheap because they are used in many different fields of the technology market. Therefore, the fabrication of gate insulators with cheap methods is important for electronic market. The solution-based processable polymer dielectrics can be grown by printing, spin coating, and spray pyrolysis instead of vacuum deposition [13]. Organic gate dielectric layers, which are other parts of OFETs, have been intensively utilized. One of these organic insulators, transparent thermoplastic polystyrene polymer is performed as an attractive alternative for gate insulators because of its numerous features such as flexibility, nontoxicity, inexpensive and low-temperature processability [14, 15]. The high-quality interface can be achieved in OFETs using polymer dielectrics [16]. There are not many studies in the literature about pentacene OFET with polystyrene polymer gate [17-19]. One of those researches is studied by Sung-woo lee et al. [15]. They investigated the effect of the molecular weight of polystyrene on electrical properties of pentacene-based transistors. Their study exhibits that a polymeric dielectric with higher molecular weight is a promising insulator for achieving superior performance OFETs because of low leakage currents between the gate contact and active layer. Also, they obtained high drain current during device operation because of bigger pentacene grains. Jae Hoon Park et al. [20] fabricated pentacene based OFET with polystyrene gate dielectric. They investigated the effect of the deposition rate of the pentacene on electrical performance of OFETs. They obtained 2×10^{-6} cm^2/Vs, 4.1×10^{-3} cm^2/Vs and 0.16 cm^2/Vs mobility values for 0.5 A°/s, 1.0 A°/s, 2.5 A°/s deposition rate of pentacene, respectively. But the interaction of polystyrene-based pentacene OFET with light has been rarely studied. In this work, we fabricated the pentacene based phototransistor having a polystyrene gate dielectric. The electrical and photosensitive properties of this OFET were investigated at room temperature. Also, scanning electron microscopy (SEM) was used to characterize the morphology of polystyrene and pentacene active layers.

2. Materials and Methods

In this study, we fabricated pentacene based field-effect transistor with top contact bottom gate architecture. Firstly, Indium tin oxide (ITO) was cleaned with deionized water, ethanol, and acetone, respectively. Polystyrene polymer was dissolved in toluene (10 wt. %) to fabricate gate insulator layer. Then, the prepared polystyrene solution was grown on ITO by spin coating method. The spin speed and time of spin coater was fixed at 1000 rpm and 60 s, respectively. The polystyrene coated ITO was baked at 100 °C under vacuum. The thicknesses of the polystyrene films were obtained as 820 nm from a cross-section of SEM image. Then, 50 nm thick pentacene semiconductor layer was evaporated on the polystyrene insulator by thermal evaporation method under high vacuum (~10^{-6} Torr). Finally, 100 nm gold was evaporated on pentacene active layer with using shadow mask to achieve source-drain electrodes (channel length 50μm, channel width 1000μm). Keithley 4200-SCS semiconductor characterization system was performed to characterize electrical performance of OFET under dark and illumination. Figure 1(a), 1(b) and 1(c) show the schematic structure of OFET, the image of OFET contact which taken from the electrical probe station and the real image of fabricated OFET, respectively.

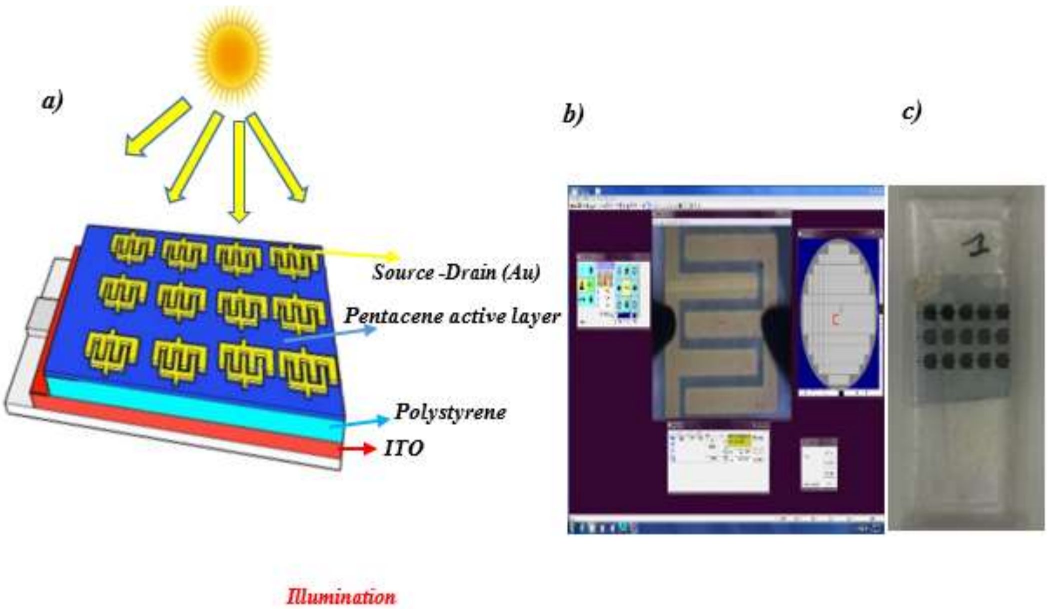

Figure 1. (a) The schematic structure of OFET **(b)** The image of OFET contact which taken from the electrical probe station **(c)** The real image of fabricated OFET

3. Results and Discussion

The surface morphology of the dielectric and active layer was examined by SEM. Figure 2 indicates (a) the surface image of polystyrene, (b) the cross-section of polystyrene and (c) the surface image of pentacene active layer taken at 5×10^4 magnifications, respectively. From these figures, it can be seen that the surface of the polystyrene film is very smooth and homogenous. It is thought that the roughness of the insulator layers decreases the charge transport mobilities in the organic semiconductors as it causes disorderliness in the accumulation layer [21]. Therefore, bottom-gate OFETs need to have a smooth insulator layer to improve their electrical performance. The SEM micrograph of the pentacene film indicates that the grains of pentacene are approximately 80 nm and are randomly distributed with clear grain boundaries.

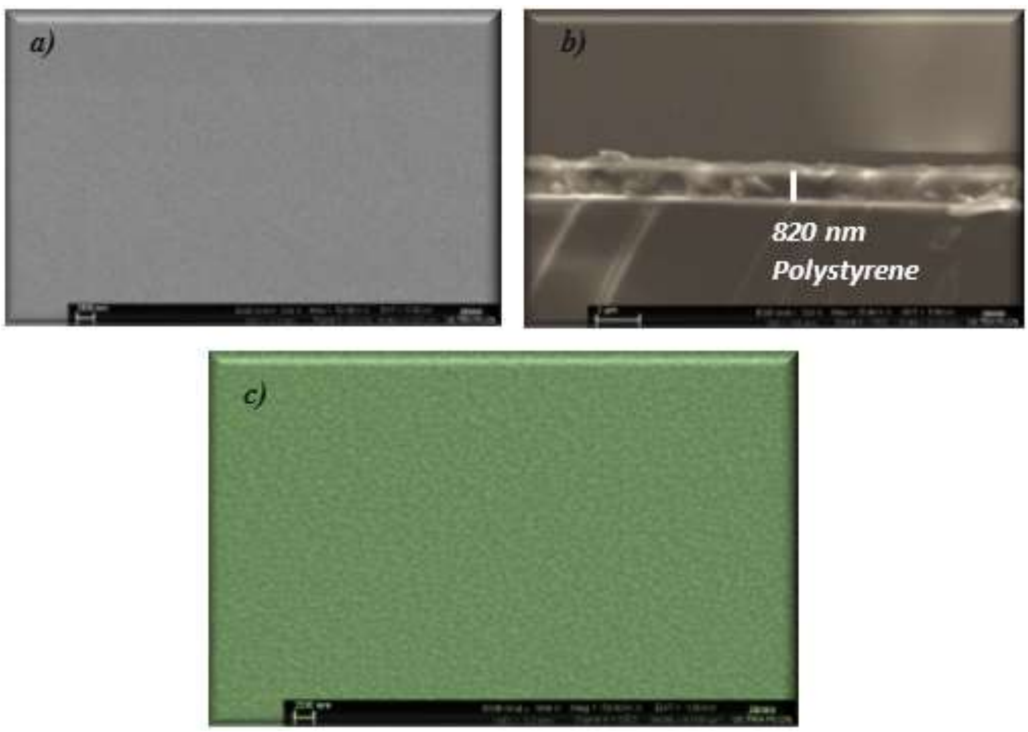

Figure 2. SEM image of (a) polystyrene (b) cross-section of polystyrene (c) pentacene active layer

The output characteristic of OFET for different gate voltage is illustrated in Figure 3(a). As expected, the output characteristic of OFET consists of linear and saturation current region. The drain current firstly increases linearly, then reaches saturation due to pinch-off. The response of the OFET to the negative V_{gs} indicates that the pentacene has a p-type nature. In this paper, we extracted the saturation field-effect mobility (μ_{sat}) and other key electrical parameters, which allow us to evaluate the performance of the device, from the typical transfer characteristics of OFET under a dark condition at room temperature. The transfer characteristic of OFET (V_{ds}= -30V) was plotted to calculate some electrical parameters of OFET such as on/off ratio, Vth and μ_{sat} and shown in Figure 3(b). The drain-source current (I_{ds}) of OFET can be expressed by the following equation (1) [8];

$$I_{ds} = \frac{\mu_{sat} C_i W}{2L} \left(V_{gs} - V_{th}\right)^2 \quad (1)$$

Where C_i, L, W, Vth, and Vgs are referring to the capacitance of the insulating layer, channel length, channel width, threshold voltage, and gate voltage, respectively. The on/off ratio, Vth and μ_{sat} of OFET were found to be ~10^2, -22V and 5×10^{-3} cm^2/Vs, respectively. The threshold voltage, on/off ratio, and mobility respectively are parameters that define the voltage required for the creation of the conductive channel, the difference between the current of on state and the current of off state and how fast an electron can move. It is desirable for high performance OFETs that the mobility and on/off ratio are high, and threshold voltage is close to zero. The negative Vth value shows that OFET works in an enhancement mode. The negative Vgs is required to form the conductive channel between source and drain in an enhancement mode.

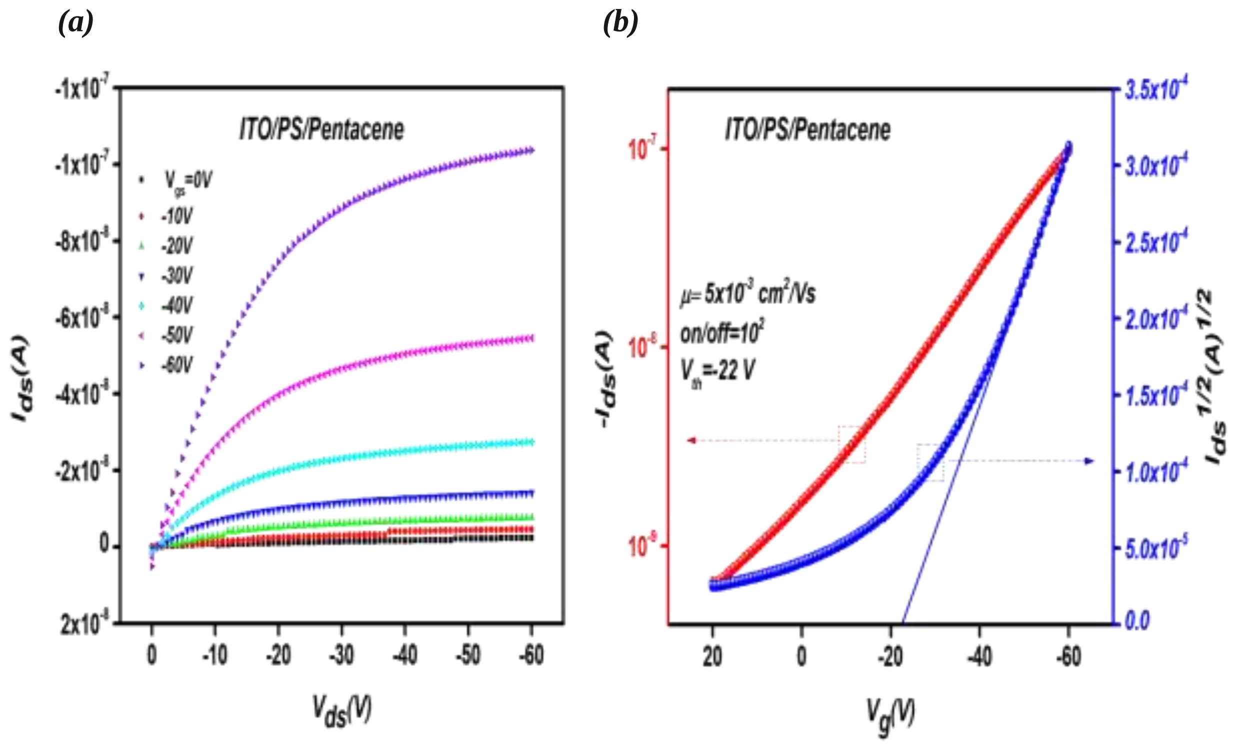

Figure 3. a) The output characteristic of OFET for different gate voltage **b)** The transfer characteristics of OFET for a certain drain voltage

In addition, polystyrene organic insulators have been greatly used for bilayer insulators in pentacene based transistors [14, 22, 23]. When the literature is examined, it shows that OFETs with the same active layer may have different mobility values. Different mobility values of OFETs with the same active layer can be explained that the mobility of OFETs is not only related to the semiconductor layers but also on the interface properties and insulators layers [24]. Figure 4(a) indicates the drain current of the OFET (at V_{gs} = 0 V) under various illumination intensities. When the photons, whose energies are higher than pentacene optical band gap energy, are absorbed by active layer, charge pairs (exciton) occur. These charges contribute drain-source current under illumination with external electric field, so drain current increases with illumination. The systematic increase of drain current with light intensity indicates that the light can serve as an additional new terminal to control current for OFET [25]. The OFET clearly shows photoresponsive behavior. The photoresponsivity (R) and photosensitivity (P) are two main optoelectrical parameters to detect light for phototransistors, which are defined by the following relations [26];

$$\mathrm{P} = \frac{I_{ph}}{I_{dark}} = \frac{I_{ill} - I_{dark}}{I_{dark}} \tag{2}$$

$$R_{phr} = \frac{I_{ph}}{P_{opt}} = \frac{I_{ill} - I_{dark}}{B.A} \tag{3}$$

Where I_{ph} is photocurrent, P_{opt} is the power of incident illumination, B is illumination intensity, A is the area of the channel, I_{ill} and I_{dark} are referring to the drain current under the light and the dark. The photosensitivity and photoresponsivity of OFET with various illumination intensities are shown in Figure 4(b).

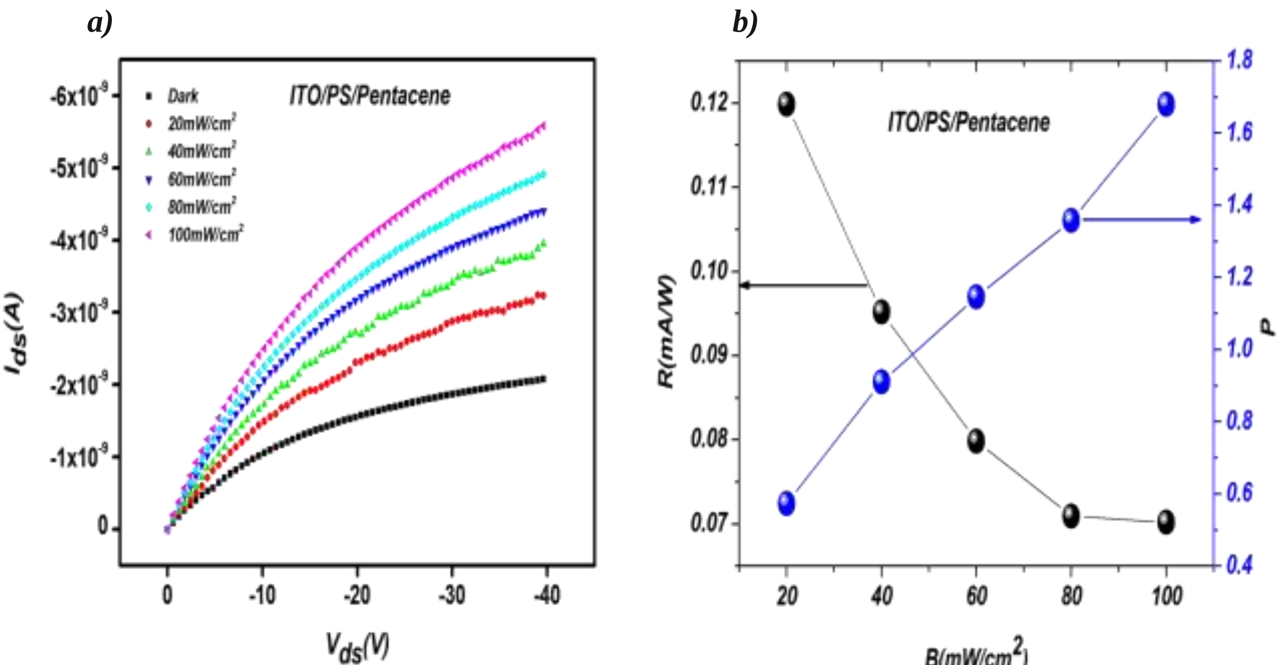

Figure 4. (a) The Output characteristics and **(b)** the photosensitivity and photoresponsivity values of OFET with various illumination intensities

It is observed that the P value of OFET increases with the light intensity from 0.5 to 1.6 under V_{gs}= 0V. When the photoresponsivity characteristic of OFET is examined, it is seen that the values of photoresponsivity of OFET decrease with increasing light intensity. The decreasing of photoresponsivity with increasing illumination intensity is often observed in detectors where nanostructured materials such as colloidal quantum dots and MoS_2 are used as active layers [27]. This effect may be related to the changing of photogenerated carriers' numbers under high photon flow. This high photon flow is based on the saturation of recombination/trap states or the Auger process. Also, these processes affect the lifetime of the carriers created under lighting [28]. These results show that the pentacene-based transistor with polystyrene gate insulator can be used as a photosensor because of its light sensitivity. When the literature is examined, it is seen that pentacene based photo transistors display different behaviors under illumination. For example, Yao et al. [29] fabricated two traditional single layer pentacene based phototransistors. In the first phototransistor, only the gold was used as ohmic contact on pentacene active layer. In the other phototransistor, C60 buffer layer was inserted between gold and pentacene active layer. The photoresponsivity values for pentacene based transistors under 0.2 $mWcm^{-2}$ light intensity were obtained 4.27 A/W and 0.7 A/W, with and without C60 buffer layer electrode, respectively. The photoresponsivity value for Pentacene OFET with 300 nm SiO_2 dielectric layer was obtained ~1 A/W under 650 nm light with 9.5 $mWcm^{-2}$ light intensity by Noh et al. [30]. In another study by Kim et al. [31], They found that the drain current of OFET measured under 13 $mWcm^{-2}$ light intensity was lower than the current measured in the dark. This decreasing drain current of OFET under visible irradiation was ascribed to the degradation of the crystal structure of the pentacene active layer [32]. The examination of the photocurrent provides a further understanding of the processes of recombination. This type of process can be analyzed by plotting the graph of the photocurrent versus light intensity B with the exponential γ power factor ($I_{ph} \propto B^{\gamma}$) [33]. Where the value of power factor γ is a term that corresponds the recombination mechanism in active layers of OFETs. The γ can be extracted from the slopes of the $\log(I_{ph})$ vs. $\log(B)$ plots. When the γ=0.5 and γ=1, the recombination processes of OFET can be explained with bimolecular recombination process and monomolecular recombination process, respectively [33, 34]. When the value of γ is between 0.5 and 1, it indicates the presence of a steady distribution of trapping centers in the mobility gap of the materials [35]. The bimolecular recombination is the process of direct recombination of photo-generated holes and electrons in the valence band (tail) and conduction band (tail). The monomolecular recombination process occurs when the recombination centers provide control over the lifetime of photogenerated carriers [36].

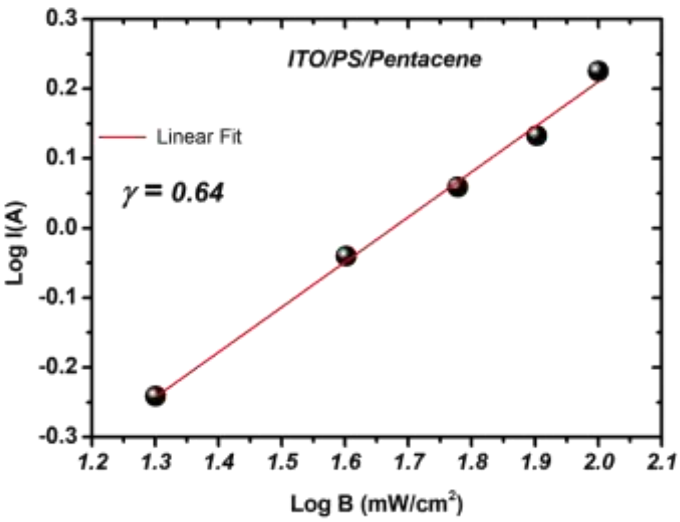

Figure 5. The $\log(I_{ph})$ vs. $\log(B)$ for ITO/PS/Pentacene OFET

Therefore, the $\log(I_{ph})$ vs. $\log(B)$ was plotted and shown in Figure 5 to calculate the γ. The γ value for pentacene based OFET was calculated as 0.64. This value indicates the presence of a continuous distribution of trapping centers in the mobility gap of the active layer.

4. Conclusions

We have examined the electrical performance of pentacene-based transistor with polystyrene organic insulator. The mobility value and on/off ratio of the transistor were found 5×10^{-3} cm^2/Vs and $\sim10^2$, respectively. In addition, photo-sensing characteristics of OFET were investigated in the visible-light region. Also, the photosensitivity and photoresponsivity of OFET were investigated under various visible illumination intensities. The photosensitivity value of OFET increases with the light intensity from 0.5 to 1.6 under Vgs= 0V. The photoresponsivity values of transistor decreased with increasing illumination intensity due to the saturation of recombination/trap states or the Auger process. Also, the fabricated OFET is sensitive to light and can be used as a photosensor.

Authors' Contributions

Serif RUZGAR conceptualization, data curation, formal analysis, writing - original draft, writing-review & editing. Mujdat CAGLAR conceptualization, data curation, formal analysis, writing-original draft, writing-review & editing.

Statement of Conflicts of Interest

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The author declares that this study complies with Research and Publication Ethics.

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