

The Study of Effect of the Active Layer Thickness on the Electrical properties of Organic Thin Film Transistor.

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Abstract:

In the present work, organic field effect transistor in TG-BC configuration was fabricated of Poly(3-hexylthiophene-2,5-diyl) (P3HT) as an active layer, and polyvinyl alcohol (PVA) as a gate dielectric layer. OFET was made at AL/PVA/P3HT/Au structure in constant conductance channel width ($W=1\text{mm}$) and length ($L=60\mu\text{m}$). The dielectric layer was deposited in constant revolution speed (1000rpm) by spin coating method, While the semiconducting polymer was deposited in multi revolution speeds (1000, 1500, 2000, 2500, 3000) rpm to obtain a different active layer thickness. All devices were worked in enhancement or accumulation mode. The best characteristic of the organic field effect transistor is when the thickness of an active layer corresponding to (2500rpm), which has the highest saturation mobility value ($5.86 \times 10^{-3} \text{ cm}^2/\text{Vs}$) and ($I_{\text{on}}/I_{\text{off}} = 786$), and lowest threshold voltage (-22V) and channel resistance ($9.57 \times 10^5 \Omega$).

Keywords: Organic field effect transistor OFET, TG-BC, Poly(3-hexylthiophene-2,5-diyl) (P3HT), Polyvinyl alcohol (PVA), Thin film, Mobility, Threshold voltage, Channel resistant.

دراسة تأثير سمك الطبقة الفعالة على الخصائص الكهربائية لترانزستور

تأثير المجال العضوي

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تم في هذه الدراسة تصنيع ترانزستور تأثير المجال العضوي بالتركيب TG-BC، وذلك باستخدام البوليمر P3HT لتشكيل الطبقة الفعالة والبوليمر PVA كطبقة عازلة للبوابة. تم تثبيت كل من طول قناة التوصيل ($L=60\mu\text{m}$) وعرضها ($W=1\text{mm}$) وسمك الطبقة العازلة للبوابة عند سرعة الدوران (1000rpm) باستخدام طريقة الطلاء بالبرم لترسيب الأغشية الرقيقة، بينما تم ترسيب الطبقة الفعالة بسرعات دوران مختلفة (1000, 1500, 2000, 2500, 3000 rpm). بينت نتائج قياس ميزتي الخرج والتحويل ان جميع ترانزستورات المصنعة هي من النوع التعزيزي (او التجميعي) (enhancement or accumulation mode). اظهرت مقارنة المعاملات الكهربائية المحسوبة للترانزستورات ان السمك الأمثل للطبقة الفعالة عند ظروف التصنيع المتبعة هي عند السمك المقابل لسرعة الدوران (2500rpm)، اذ كانت معاملات الترانزستور الأفضل هي:

$$(\mu_{\text{sat}}=5.86 \times 10^{-3} \text{ cm}^2/\text{Vs}),$$

$$(I_{\text{on}}/I_{\text{off}}=786), (V_{\text{th}}=-22\text{V}), (R_{\text{ch}}=9.57 \times 10^5 \Omega)$$

Introduction:

Organic electronics is a branch of electronics based on the organic materials as a effective medium in the manufacture of electronic devices, it's also called plastic electronics, which are flexible, transparent, light weight, large area and cheap making cost. The use of organic materials to build electronic devices was the reason for the growth of our electronic world, and most of its products were environmentally friendly and low-energy consumption in both manufacturing and operation processes. Organic materials have been used in manufacturing many electronic devices such as flexible displays, processors & memories, electronic textiles, radio-frequency identification (RFID), sensors, As well as biochemical detectors, thin films batteries, organic light emitting effect transistors (OLE-FET) and other applications.[1-5]

In the past few decades, researchers have focused on the possibility of using organic materials to manufacturing of the field effect transistor for new applications, because of their efficient applications in low cost integrated circuits that can be manufactured in large areas on different substrate, even flexible type. Research has been accelerated in the manufacture of organic semiconductors and the development of electronic device manufacturing methods. Studies have begun to investigate the improvement of the properties of organic semiconductors such as increasing the electrical conductivity of these materials. These efforts have resulted in the manufacture of the organic field effect transistor with a

high current ratio, high mobilities and low operating voltage.[6-8]

Thin Film Transistors-TFTs is the device that uses the electric field to adjust the electrical conductivity of the conduction channel located on the interface between the insulating layer and the semiconductor layer. Therefore, it is a field effect transistor (FET), similar to that known metal oxide field effect transistors (MOSFET), and is the basic structure of modern integrated circuits. The evolution date of both TFTs and MOSFETs is parallel at a time. Today, OFET transistors are made on different bases and even on flexible. Transistors are involved in the manufacture of many devices such as video equipment, flexible displays and small screens on the traditional glass bases of the mobile phone and other applications growing rapidly, such as LCD display screens, smart cards, memory cards, electronic textile and others. The organic field transistor technology can be ideal for the infrastructure of these applications and other applications because of the close compatibility of OLED and OFET materials and their good mechanical properties. The transistors are the basic brick in modern circuits and are used as a amplifier tool or switching key. The effect of the field is the phenomenon in which the electrical conductivity of semiconductors is changed by applying an electric field on its surface. The electric field is applied through a metal gate in the device. The field effect transistors mainly consist of three electrodes: Source-S, Drain-D, Gate-G , As well as a layer of semiconductor and insulating layer between the semiconductor and the gate. Figure (1) shows the general structure (in Bottom Gate-Top Contact, (BG-TC)) of the field effect transistor. The OFET is a two-dimensional structure because the insulating and semiconductor layers are

formed in the form of two-dimensional thin films, due to the linear composition of many of the semiconductor materials used. In addition to the use of organic semiconductors and organic insulating material, all components of the transistor can be replaced with organic materials.[9-12]

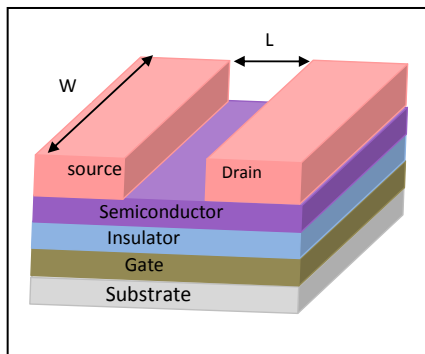


Figure (1) the general structure of the field effect transistor.

In organic field effect transistor for saturation region, the charge carrier mobility (μ_{sat}) is:[13]

$$\mu_{sat} = \frac{2L}{WC_i} \left(\frac{\partial \sqrt{I_{ds}}}{\partial V_{gs}} \right)^2 \dots \dots \dots (1)$$

Where L, W are the conductance channel length and width, I_{ds} is channel current, V_{gs} is the gate-source voltage and C_i is the electrical capacitor per unit area of gate dielectric layer. The conductance channel resistance (R_{ch}) is given by:[14]

$$R_{ch} = \frac{L}{W\mu C_i (V_{gs} - V_{th})} \dots \dots \dots (2)$$

Where V_{th} is the threshold voltage.

The soluble polymers which can dissolve in solvents was contributed in

development of multilayer devices by solution deposition methods in low temperature on a various types of substrates so as to flexible substrate. The thiophenes roots one of the most electronics organic semiconductors. The dielectric layer can be cross-linked or consist of polymer blends or doped polymer to manufacturing a high capacitance layer to limiting of leakage currents and providing a good surface to growth a semiconductor layer. Figure (2) illustrates the chemical structures of some dielectric polymers which used as gate dielectric layers in OFETs.[4, 15-18]

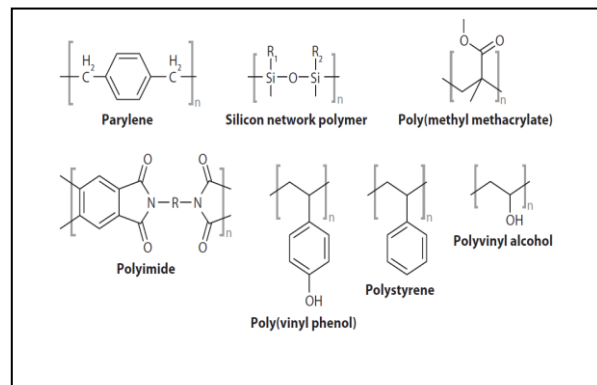


Figure (2) the chemical structures of some dielectric polymers.[19]

Materials and Methods:

Regioregular polymer Poly(3-hexylthiophene-2,5-diyl) (P3HT), product batch number M102 electronic grade, was purchased from Ossila Limited Co., UK, average molecular weight Mw 65200 and Mn 29600, >95.7% head-to-tail regioregularity, molecular formula $\{(C_{10}H_{14}S)_n\}$ is a conjugated polymer was used in this research, figure (3) shows its chemical structure. P3HT solution was prepared in 1,2-dichlorobenzene (from Sigma-Aldrich) in 10 mg/ml concentration by stirring at 60°C for 15 minutes. Finally, after cooling to room temperature, the

solutions was filtered with syringe filter of size 200 nm.

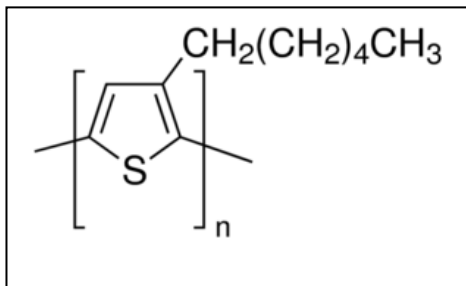


Figure (3): Chemical structure of P3HT.

Polyvinyl alcohol (PVA) with an average molecular weight within of (85,000-124,000) g/m, viscosity (4% aqueous solution at 20°C): 28-32 cps, hydrolysis degree (99%) was obtained from Sigma-Aldrich-India. It has a chemical structure ($[\text{CH}_2\text{-CHOH}]_n$ - as in figure (2)). Aluminum and gold of purity (99.99%) was provided from Sigma-Aldrich for deposition the electrodes. PVA solution was prepared in deionized water at 70 mg/ml concentration by stirring at 90°C for 8 hours. Finally, after slow cooling to room temperature, the solutions were filtered by syringe filter (220 nm).

In cleaning process of substrates, it's received a multistep solvent clean by ultrasonication technique; 5 min in isopropyl alcohol, 5 min in acetone and 5 min in deionized water, then substrates dried in oven at 90°C for 1 hour, then cooling to reach room temperature. A very thin aluminum layer than a gold source and drain electrode have deposited by thermal technique on glass substrates by using a local made mask with conducting channel constant distance of ($W/L=1\text{mm}/60\mu\text{m}$). P3HT thin films were deposited on electrodes by using the spin coating method in multi revolution speeds (1000,1500, 2000, 2500, 3000)rpm for one minute to obtaining a different thickness of the active layer thin film, and annealed to

120°C for 10 minutes in laboratory oven. The gate dielectric layer deposited by using spin coating at constant revolution speed (1000rpm), and annealed at 70°C for 3 hours. The upper aluminum electrode (gate electrode) was deposited by evaporation method under vacuum (10^{-5} torr), to complete an OFET in Top Gate- Bottom Contact (TG-BC) configuration.

The output and transfer characterizations of organic thin film transistor was measured in darkness by using couple of Keithley-2400 device which are controlling by a computing system. The measurements done at darkness and room temperature.

Results and Discussion:

Figures (5-9) show the results of the measurement; (a) the output characteristic and (b,c) transfer characteristic of these organic transistors, which show that the changing of the active layer thickness in the transistor configuration has a significant effect on the electrical properties of this device. Where its electrical capacitor per unit area for AL/PVA/Au sandwich structure at constant frequency (1KHz) is ($223\text{ nF}/\text{cm}^2$).

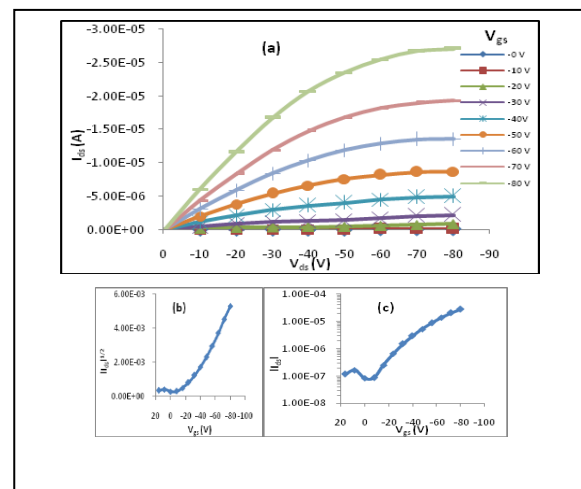


figure (5); a) output and b,c) transfer characteristic at ($V_{ds}=-70\text{V}$) and active layer (1000rpm).

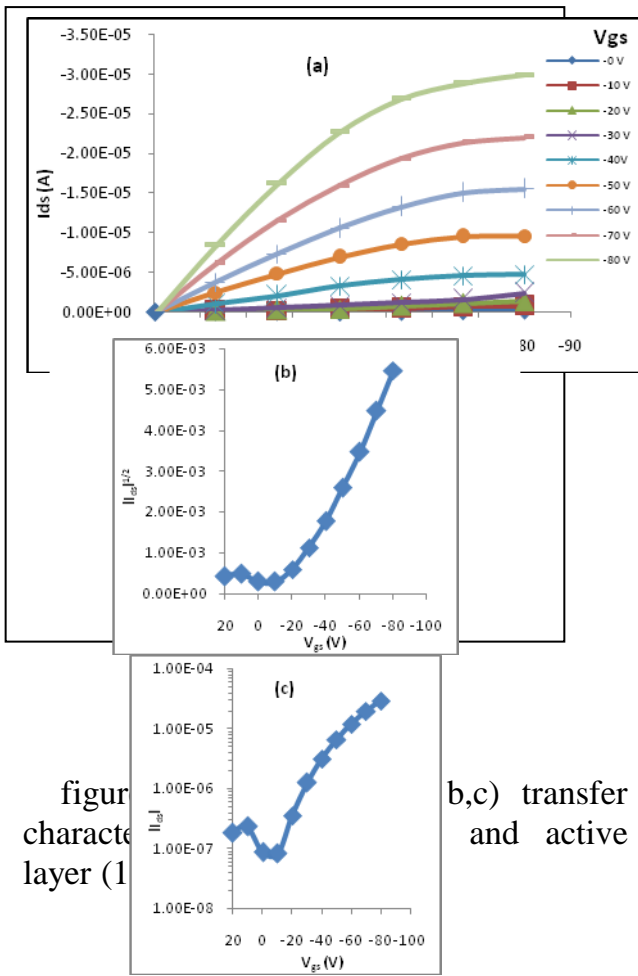


figure character layer (1

b,c) transfer and active layer

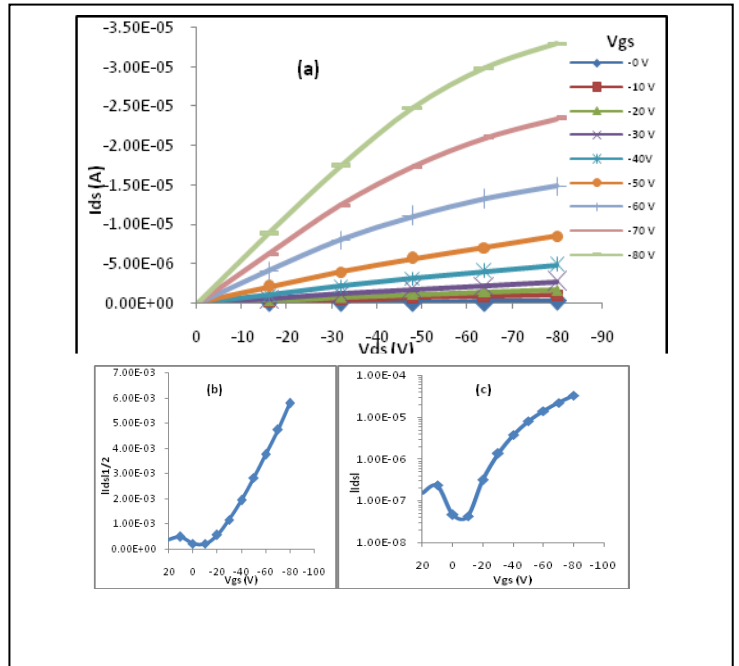
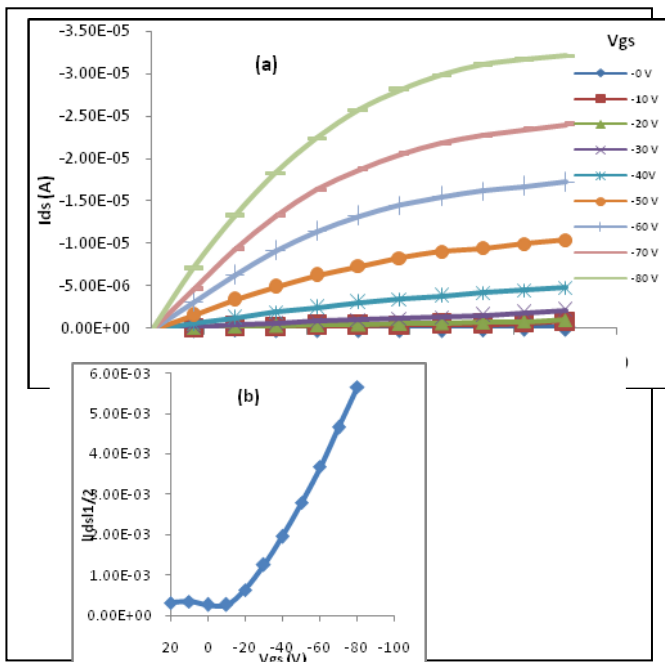


figure (8);a) output and b,c) transfer characteristic at ($V_{ds}=-70V$) and active layer (2500rpm).



c

and b,c) transfer (0V) and active

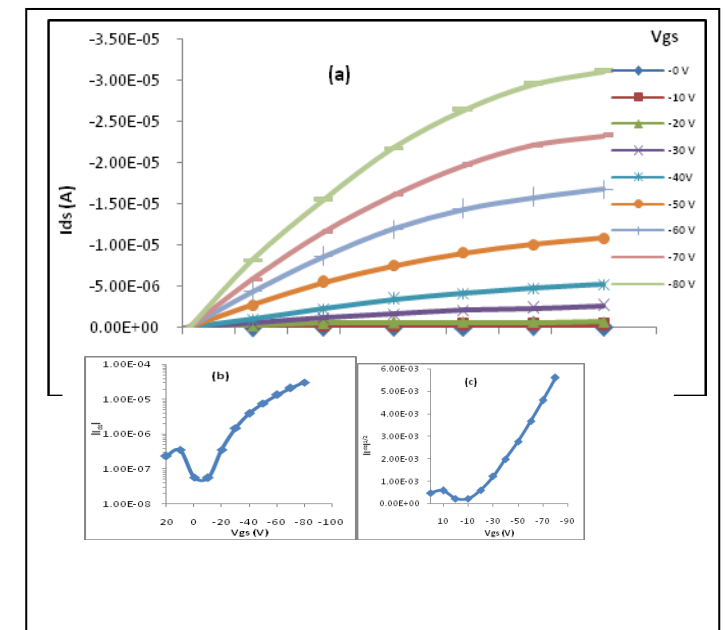


figure (9);a) output and b,c) transfer characteristic at ($V_{ds}=-70V$) and active layer (3000rpm).

The main parameters of OFETs were calculated by using the equations (1,2) and transfer characterizations. The charge carrier mobility at saturation, the resistance of the conduction channel, as well as the threshold voltage and the ratio between the operating current and off current, were calculated directly from the conversion of the transistor current. Figures (10-13) shown the obtained results for these parameters of transactions versus the active layer deposition revolution speed.

It is noticeable from these results that all devices were enhancement mode, and the resistance of the conduction channel is increased by increasing of active layer thickness due to the increased roughness of the surface of the effective layer with decreasing the revolution speed of the spin coating deposition method. This increasing of roughness at interface where the conduction channel is formed will results a charge traps that inhibit the transfer of charge carriers in the interface between the active layer and the gate insulator layer, which negatively affects the channel current value and the mobility of the charge carriers and increasing the threshold voltage in the organic field effect transistor. In addition to, the reduce of the thickness of the semiconductor layer is an auxiliary factor to increasing the electrical conductivity, because its reducing the defects of crystalline and increase the regularity of polymer chains within the polymeric lattice, as well as, increasing the overlap between the orbits of π orbital, which increases the mobility of charge carriers.[20-25]

While the negative threshold voltage decreasing with decrease of active layer

thickness, as a results of decreasing of charge carriers traps in the conduction channel. As that, the fluctuation of I_{on}/I_{off} is may be related to either changing in the contact resistance or due to the charge carriers mobility, which are affective on I_{on} value. This result was correspond to previous studies. [26-30]

Conclusions:

The results shown that all OFET devices which made at AL/PVA/P3HT/Au structure, and were manufactured in a constant conduction channel width ($W=1mm$) and length ($L=60\mu m$), were operating in enhancement (accumulation) mode.

We find from above results that the best characteristic of the organic field effect transistor is when the thickness of an active layer corresponding to the revolution speed (2500rpm), which has the highest saturation mobility value ($5.86 \times 10^{-3} \text{ cm}^2/\text{Vs}$) and ($I_{on}/I_{off}=786$), and lowest threshold voltage ($-22V$) and channel resistance ($9.57 \times 10^5 \Omega$) between the values of other samples.

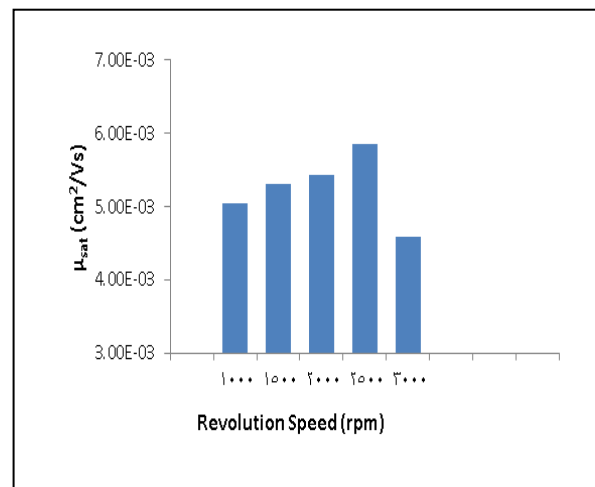


Figure (10): The saturation mobility of OFET vs. deposition revolution speed of P3HT.

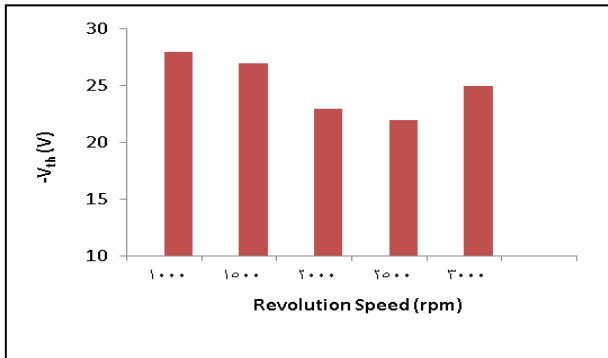


Figure (11): The threshold voltage of OFET vs. deposition revolution speed of P3HT.

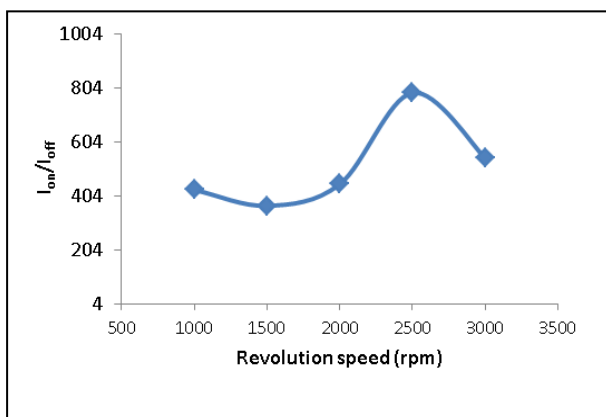


Figure (12): I_{on}/I_{off} ratio of OFET vs. deposition revolution speed of P3HT.

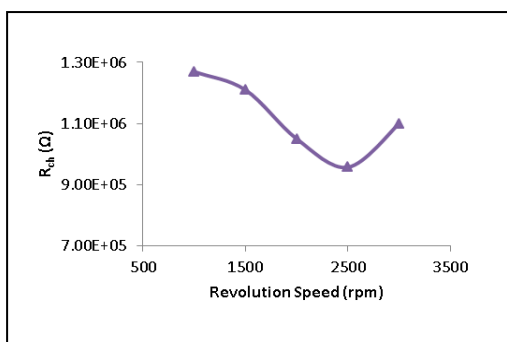


Figure (13): The channel resistance of OFET vs. deposition revolution speed of P3HT.

References:

- 1- W. L. Leong, P. S. Lee, A. Lohani, Y. M. Lam, T. Chen, S. Zhang, A. Dodabalapur and S.G. Mhaisalkar, *Adv. Mater.*, 20, 2325–2331, (2008).
- 2- M. Stoppa and A. Chiolerio, *Sensors*, 14, 11957-11992, (2014).
- 3- S. Muench, A. Wild, C. Friebe, B. Häupler, T. Janoschka, and U.S. Schubert, *Chem. Rev.* 116, 9438–9484, (2016).
- 4- B. B. Patowary, *Inter. J. of Adv. Res. in Elec., Electronics and Instrumentation Engineering*, Vol. 3, Issue 5, 9351-9361, (2014)
- 5- C. Yumusak, M. Abbas, N. Sariciftci, *Journal of Luminescence* 134, 107–112, (2013).
- 6- S. Kumar and A. Dhar, *Procedia Engineering*, science direct, 141, 78–82, (2016).
- 7- H. Wang and D. Yan, *Organic NPG Asia Mater.* 2, 2, 69–78, (2010).
- 8- C. Wang, H. Dong, W. Hu, Y. Liu and D. Zhu, *Chem. Rev.*, Vol. 112, pp. 2208-67, (2012).
- 9- G. Nisato, D. Lupo, S. Ganz, Taylor and Francis Group, 2-4, (2016).
- 10- I. Kymissis, *Spriger*, 1-3, (2008).
- 11- R. F. Pierret, 525, (1996).
- 12- A. L. Briseno, M. Roberts, M. Ling, H. Moon, E. J. Nemanick and Z. Bao, *J. AM. CHEM. SOC.*, 128, 3880-3881, (2006).
- 13- H. Klauk, *Chem. Soc. Rev.*, 39, 2643–2666, (2010).
- 14- W. Ou-Yang, M. Weis, T. Manaka and M. Iwamoto, *Sci. Direct, Physics Procedia*, 14, 198–203, (2011).

- 15- C. Di, Gui Yu, Y. Liu, Y. Guo, Y. Wang, W. Wu and Daoben Zhu, *Adv. Mater.*, 20, 1286–1290, (. 2008).
- 16- G. Horowitz, *Adv. Mater.*, 10, 5, 365, (1998).
- 17- H. Klauk, Wiley-VCH, 367-380, (2006).
- 18- H. Klauk, *Chem. Soc. Rev.*, 39, 2643–2666, (2010).
- 19- D. Kahng, M. M. Atalla, IRE Solid-State Devices Research Conference, Carnegie Institute of Technology, Pittsburgh, PA (1960).
- 20- S. Kirchmeyer and K. Hecker , *Organic and Printed Electronics*, 11, (2013).
- 21- S. Cho and K. Leea, *JOURNAL OF APPLIED PHYSICS*, 100, 114503, (2006).
- 22- J. Y. Na, B. Kang, D. H. Sin, K. Cho & Y. D. Park, *Scientific. Rep.*, 5,13288, (2015).
- 23- N. Koch, Wiley-VCH Verlag-Chem.Phys., 8, 1438 – 1455, (2007).
- 24- P. Pacher, A. Lex, V. Proschek, H. Etschmaier, E. Tchernychova, M. Sezen, U. Scherf, W. Grogger, G. Trimmel, C. Slugovc, and E. Zojer, *Adv. Mater.*, 20, 3143–3148, (2008).
- 25- B. Park, A. Aiyar, J. Hong, and E. Reichmanis, *American Chemical Society, ACS Appl. Mater. Interfaces*, 3, 1574-1580, (2011).
- 26- R. Schroeder, L. A. Majewski, and M. Grell, *Applied Physics Letters*, 84, 6, (2004).
- 27- H. Jia, S. Gowrisanker, G. K. Pant, R. M. Wallace, and B. E. Gnade, *J. of Vacuum Science & Technology A*, 24, 1228, (2006).
- 28- Y. Ran, L. ZhiDong, H. YuFeng, C. ShaoBo, T. Feng, H. YanBing & L. XiaoJun, *Scie. China-Technological Sciences*, 57, 6, 1142–1146, (2014).
- 29- W. Wang, D. Ma, S. Pan, and Y. Yang, *Appl. Phys. Lett.* 101, 033303, (2012).
- 30- H. Jia, S. Gowrisanker, G. K. Pant, R. M. Wallace, and B. E. Gnade, *Journal of Vacuum Science & Technology A* 24, 1228 (2006).