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Performance Comparison of Low-Voltage non-Ionic Gel Organic Field Effect Transistors with Gold and PEDOT:PSS Gate Electrodes

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Abstract*— Low-voltage non-ionic gel organic-field effect transistors (NIGOFETs) with two kinds of gate electrode materials namely gold (Au) and poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) formulation were fabricated in top-gate bottom-contact geometry to investigate the effects of gate electrodes on the electrical performance of the OFETs. In addition, three kinds of gate dielectrics were used for both types of transistors to understand the effects more thoroughly. As a result, it can be deduced from the data that NIGOFETs with Au gate electrodes (Au-NIGOFETs) display better performance considering higher mobility and on-to-off current ratio (I_{ON}/I_{OFF}) as well as lower Subthreshold Swing (SS) of them. Besides, the threshold voltage (V_{TH}) effects-free drain currents (I_{DS}) of the Au-NIGOFETs surpasses those of the PEDOT:PSS formulation gated NIGOFETs (Pedot-NIGOFETs). This is probably due to having greater WF gate electrode (in our case Au) provides less injection barrier eventually leads to relatively unimpeded charge transportation. Nevertheless, Au-NIGOFETs interestingly proves to have further negative V_{TH} and lower off-current (I_{OFF}), which may be attributed to lower electrical resistivity (ρ) of the Au leading to denser charge carrier traps formation along with intensified charge carrier induction at the semiconductor-dielectric interface when the gate-to-source voltage (V_{GS}) is less than V_{TH}. However, because of the same reason, when V_{GS} exceeds the V_{TH} for example, I_{DS} of Au-NIFOFET1 starts to increase in such a quick manner that enabling it to have higher I_{ON}/I_{OFF} and lower SS.

Keywords — non-ionic gel organic-field effect transistor (NIGOFET), gate electrode, work function (WF), electrical resistivity (ρ) threshold voltage (V_{TH})

I. Introduction

It is generally believed that organic-field effect transistors (OFETs) are still an interesting topic among the organic electronics community. Since reducing the operating voltages of the OFETs means that they consume less power, numerous studies using different techniques have been carried out to accomplish this goal. One of the promising techniques among them is using an electrolytic gate dielectric (EGD) so that huge effective capacitance (C_{EFF}) can be formed both in gate electrode-insulator and

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insulator-organic semiconductor interface, which eventually leading to formation of particular charge carriers in the organic semiconductor via applying a less voltage. These insulators have been studying in the literature for decades [1–5].

On the other hand, using non-ionic gel gate dielectrics (NIGDs) is another viable option, which does not only provides the devices having high performance but also brings about inexpensive designs with simple fabrication techniques. Some studies in the literature have used this technique named those kinds of transistors as non-ionic gel OFETs (NIGOFETs) and proved their feasibility [6–10]. Even though different gate electrodes were employed in these studies, resulting performance variation due to the usage of those particular gate electrodes has not introduced until now. However, as it is known, if proper materials are used, gate electrodes can affect the working of the OFETs significantly and enhance the electrical parameters of them [11]. Therefore, essential studies regarding the impact of the different gate electrode materials on the performance should be carried out to decide which materials are better candidates for being gate electrode to achieve more developed designs. Some related studies with widely used gate insulators were conducted concerning this topic [12–14]. Two of these studies used ionic electrolytes as gate insulators while the rest of them used polymer gate insulators. In one of them, Kergoat et al. proved that flat-band voltage (V_{FB}) and threshold voltage (V_{TH}) could be related to the work function (WF) of the gate electrodes and they could be reduced in the case of using higher-WF gate electrodes [14]. In the other study, Fabiano et al. showed that V_{TH}-free drain-to-source current (I_{DS}) in the output characteristics of the OFET could be improved if polyelectrolyte/gate electrode WF is larger than 4.1 eV (as for Ni and Cu). This could cause pinning at the organic semiconductor (poly(3-hexylthiophene-2,5-diyl) (P3HT))/ polyelectrolyte interface according to the positive integer charge transfer energy (EICT+) of the P3HT (4.1 eV) eventually increasing performance [12]. These studies were stressed noticeably on the impact of gate electrodes on I_{DS} and V_{TH}. However, as far as we are known, none of the work has been performed in which NIGD is used as a gate insulator and has been concentrated on the impact of different gate electrodes on the main electrical parameters of the OFET such as mobility, V_{TH}, I_{ON}/I_{OFF}, and Subthreshold Swing (SS).

Therefore, NIGOFETs with two types of gate electrodes were fabricated in this study to understand the effects of the different gate electrodes on the main electrical parameters. Since it incorporates good wetting property and high conductivity [15] as an organic conductor, transparent polymer poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) formulation was used as a first gate electrode. On the other hand, since it is known as a high WF metal, gold (Au) was chosen as a second gate electrode for comparison. Following three kinds of NIGDs (NIGD1, NIGD2, and NIGD3) were employed for each type of NIGOFETs and labeled according to their name of gate dielectrics (NIGOFET1, NIGOFET2, and NIGOFET3), Au and Pedot prefixes were added to the labels to stress the gate electrodes used in the corresponding design (Au-NIGOFETs or Pedot-NIGOFETs). Thus, totally six different kinds of devices were fabricated to help to grasp the concept thoroughly. Furthermore, regioregular P3HT (rr-P3HT) was used as an organic semiconductor in the designs because we intend to compare all devices with familiar ones in the literature in which generally P3HT is employed.

II. EXPERIMENTAL DETAILS

Transistors were fabricated using top-gate bottom-contact configuration. Interdigitated ITO substrates containing channels at 50 µm length (L) and 30 mm width (W) were purchased from Ossila ltd. The overall fabrication procedure is shown in Fig. 1. PEDOT:PSS, rr-P3HT, and NIGDs solution preparations and spin coating of the PEDOT:PSS and rr-P3HT procedures were quite similar to the one that can be found in the literature [9]. Hence, we prefer to refer the readers to relevant studies instead of repeating to explain the fabrication procedure. However, it is worth mentioning that because of the comparative reasons, Au gate electrodes were additionally fabricated in this study by depositing Au onto an ITO surface via using the thermal evaporation method unlike PEDOT:PSS and rr-P3HT, which were deposited onto an ITO surface with spin coating method. Another subject that must be stressed that the NIGD was applied onto the rr-P3HT surface quite carefully by a laboratory spatula so that as soon as the gate electrode covered the gel layer, it flattened the layer to some degree and allowed it to spread out to the entire surface homogeneous enough to form the transistor structure properly.

PEDOT:PSS and rr-P3HT solution preparations and spin coatings were performed in atmospheric conditions and all electrical characterization was carried out by Keithley 2612B SMU source meter in atmospheric conditions as well. Besides, thermal evaporation was performed in a vacuum by Nanovak thermal evaporator (NVBJ-300TH) device. Meanwhile, C_{EFF} measurements were performed by using Novocontrol impedance analyzer (Alpha-AN).

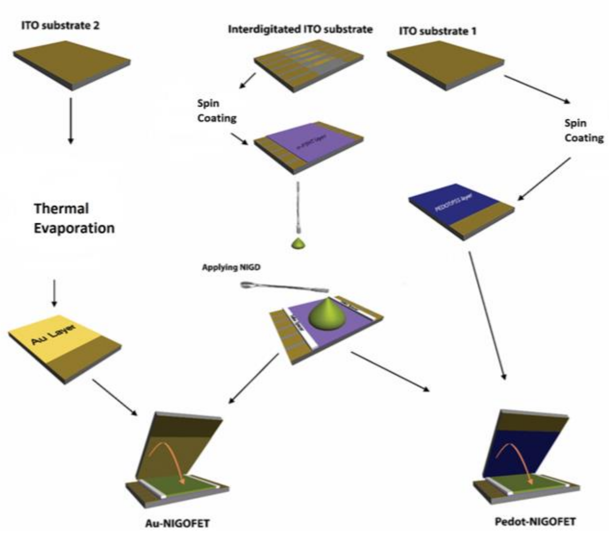

Figure1. Schematic illustration of Au and Pedot-NIGOFET fabrication.

III. Results And Discussion

Most adopted way to understand whether fabricated devices working properly as a transistor in the low-voltage range is using current-voltage (I-V) measurements. These measurements were performed to extract the output and transfer characteristics of the NIGOFETs. In this respect, I_{DS} values were obtained by sweeping the drain-to-source voltage (V_{DS}) between 0 to -1V while keeping gate-to-source voltage (V_{GS}) constant at values rising from +0.1V to -1V at 0.1V interval. Thus, all of the output characteristics of the NIGOFETs are extracted in this way and are seen in Fig. 2. Saturations after a linear region before -1V in the plots indicate that low-voltage transistor devices are formed nicely. But some issues must be addressed at this point. One of them is, for higher V_{GS}, demonstration of Pedot-NIGOFET2 positive offset I_{DS}, which may be attributed to gate induced leakage current and parasitic parallel conduction paths [16], [17]. These factors affect NIGOFET2s more severely probably because of the lower relative dielectric constant (ε_r) [9] of their NIGD2s implies weak insulation property and invites greater leakage current. At higher V_{GS}, after V_{DS} = -0.6V the other issue is, demonstration of Au-NIGOFET1 a negative offset I_{DS} due probably to migration of anions from NIGD1 to the rr-P3HT layer as a result of an electrical breakdown. Therein recombination of these anions with the holes results in a decline in I_{DS}.

The last and most significant issue is, apparently less gradual rising of the I_{DS} of the Au-NIGOFETs and reaching I_{DS} of them the value nearly two times those of the Pedot-NIGOFETs. This may be the result of Au-NIGOFETs having lower source contact resistances because of higher WF of the Au compared to that of PEDOT:PSS formulation [12]. At this point, measurements of the WF of both gate electrodes are required to verify that WF of the Au is the greater one. Unfortunately, we did not have any opportunity to measure them with a Kelvin probe microscope, instead, we estimate them with the help of investigating the literature. In this respect, because Au thermally evaporated on a substrate at high temperature, WF of the Au gate electrode is determined as approximately 5.45 eV [18]. On the other hand, WF of the PEDOT:PSS formulation gate electrode is determined as approximately 5 eV by benefiting from the website of the vendor and by referring to a study that mentioned about how to WF of the PEDOT:PSS be decreased by adding more dimethyl sulfoxide (DMSO) to it [19], [20]. Hence, WF of both gate electrodes are determined in this way and this designation supports our claim.

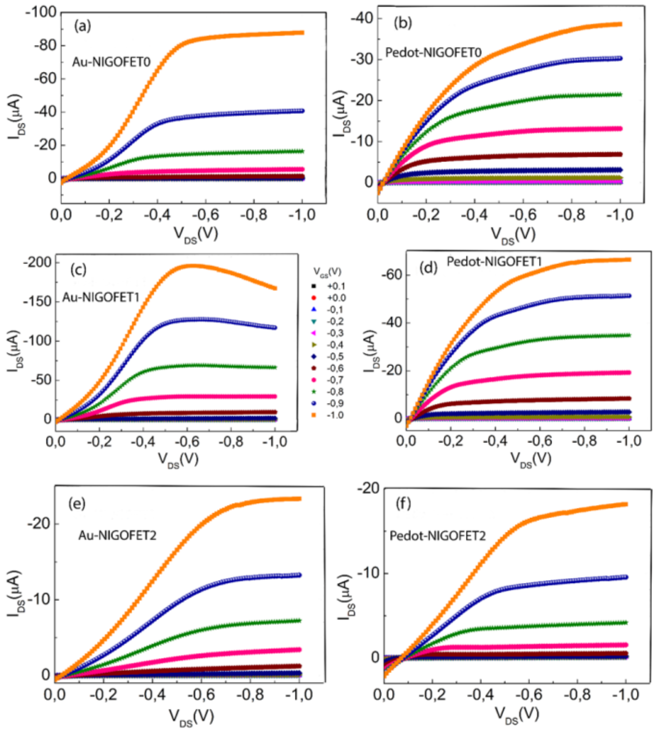

Figure 2. Output characteristics of (a) Au-NIGOFET0 (b) Pedot-NIGOFET0 (c) Au-NIGOFET1 (d) Pedot-NIGOFET1 (e) Au-NIGOFET2 (f) Pedot-NIGOFET2.

One of the important electrical parameters that can be affected by the WF of the gate electrodes is mobility that is directly proportional to I_{DS}. (V_{GS}-V_{TH}) is taken as -0.3V to exclude the effect of WF on V_{TH} to investigate the effect of WF only on I_{DS} and I_{DS} is observed from the output characteristics of both Au and Pedot-NIGOFET1, which are shown in Fig. 3. As a result, it is seen that I_{DS} of the Au-NIGOFET1 surpasses nearly four times that of the Pedot-NIGOFET1. we believe that this may be attributed to greater WF of the Au gate electrode leading to the formation of less injection barrier for holes, which boosts the charge injection at the source electrode further [12]. Since one of the variables that is directly proportional to the I_{DS} is saturation mobility (μ_{sat}), which can be found clearly in the mobility expression in equation (1) [21], it can be said that using a high WF gate electrode such as Au can enhance the mobility of the transistors as well. This enhancement is shown clearly in Table 1.

$$\mu_{sat}=\frac{I_{DS}L}{WC_{EFF}}\frac{2}{(V_{GS}-V_{TH})^2} \tag{1}$$

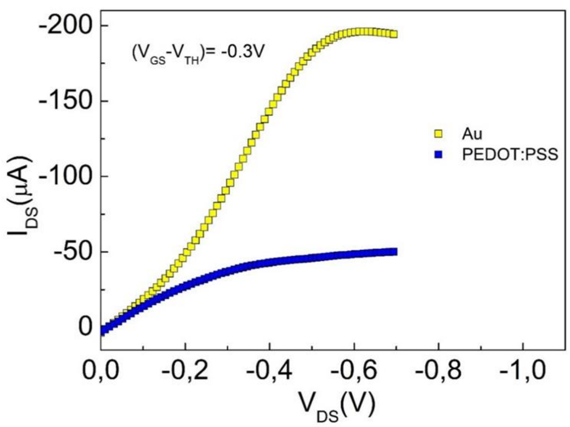

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Figure 3. Output characteristics of both Au and Pedot-NIGOFET1 at (V_{GS}-V_{TH}) = -0.3V

The WF of the gate electrodes can affect not only IDS and μ_{sat} but also V_{TH}. This means that as well as the other techniques, V_{TH} can be adjusted by changing the gate electrode material [13], [14]. V_{TH} can be expressed as equation (2) below [22]

$$V_{TH}=\frac{-qn_od}{C_{EFF}}+V_{FB} \tag{2}$$

Where q is the elementary charge, n_0 is bulk carrier density, d is the thickness of the semiconductor, C_{EFF} is the effective capacitance of the insulator layer, and V_{FB} is the flat-band voltage, which can be expressed by equation (3) below [14].

$$V_{FB}=\frac{W_M-W_S}{q}-\frac{Q_{IS}}{C_{EFF}} \tag{3}$$

Where W_M and W_S are the gate electrode and semiconductor work functions respectively and Q_{IS} is the interface charge density. If we combine these two equations, we obtain equation (4) below.

$$V_{TH}=\frac{W_M-W_S}{q}-\frac{(qn_od+Q_{IS})}{C_{EFF}} \tag{4}$$

Using above equations, for example, If V_{TH} of Au and Pedot-NIGOFET1 are compared, it can be noticed that since the same semiconductor and gate insulator were used for both devices, only the W_M and Q_{IS} variables are different for both devices and only those values could determine how much the two V_{TH} values differ from one another. Initially, considering the greater W_M of Au, it can be figured out that V_{TH} of the Au-NIGOFET1 is further positive and greater than that of the Pedot-NIGOFET1. However, Q_{IS} of the Au-NIGOFET1 is also greater one and it adds to the V_{TH} of it a negative value, which helps the V_{TH} progressing at the negative side. In this case, mathematically, it can be said that it is impossible to specify which device has a further positive V_{TH} without exactly knowing the W_M, Q_{IS}, and other variables in the equation (4). As is seen from Table 1 as well as in Fig. 4. (b) that, for all devices, V_{TH} of the Au-NIGOFETs are further negative, which may be attributed to the impact of Q_{IS} dominating the impact of W_M on the V_{TH}. This is probably due to having of Au-NIGOFETs more energy distributions of localized levels near to transport band edge, which act as shallow traps for charge carriers [23]–[25]. Considering electrical resistivity (ρ) of the PEDOT:PSS formulation is at least three orders of magnitude greater than that of the Au [26], [27], it would not be surprising that more charge carrier traps are formed as well as more charge carrier injections in the P3HT/NIGD interface of Au-NIGOFETs bringing about a delay of rising of I_{DS}. Moreover, as is seen from Fig. 4. (a), ρ of the gate electrodes not only affects the V_{TH} but also I_{OFF} and how the I_{DS} rises relative to the V_{GS} when the V_{GS} exceeds the V_{TH}. Namely, in the case of using Au as a gate electrode, when the V_{GS} lags behind the V_{TH}, more intense charge carrier traps are formed and this results in reduced I_{OFF}. When the V_{GS} exceeds the V_{TH} on the other hand, more traps become filled and I_{DS} starts to increase more rapidly until it reaches on-current (I_{ON}) at V_{GS} = -1V.

The electrical parameter that symbolizes the ratio of the above-mentioned I_{ON} to I_{OFF} is I_{ON}/I_{OFF} and the gauge of how abruptly the I_{OFF} proceed to I_{ON}, in other words, how to device respond to V_{GS} and turn on is SS. [28]. Au-NIGOFETs prove generally higher I_{ON}/I_{OFF} and lower SS as shown in Table 1 because of the lower ρ of Au as pointed out above. However, it seems that I_{ON}/I_{OFF} of Au-NIGOFET2 is the only exception to this determination. It may be correlated with the lowest ε_r property of the NIGD2 causing intense anion migration from NIGD2 to the P3HT bulk so that preventing the I_{DS} from rising more abruptly. Apart from those, the fact of same gated NIGOFETs having different I_{ON}/I_{OFF} and SS is connected with the quality of their interface and ε_r of their NIGDs. It is known that NIGD1 was selected as the best gel gate insulator among the three in our past study [9]. Therefore, showing the Au-NIGOFET1 the best performance among the transistors is expected since it possesses the best-qualified interface and higher-WF lower-ρ gate electrode.

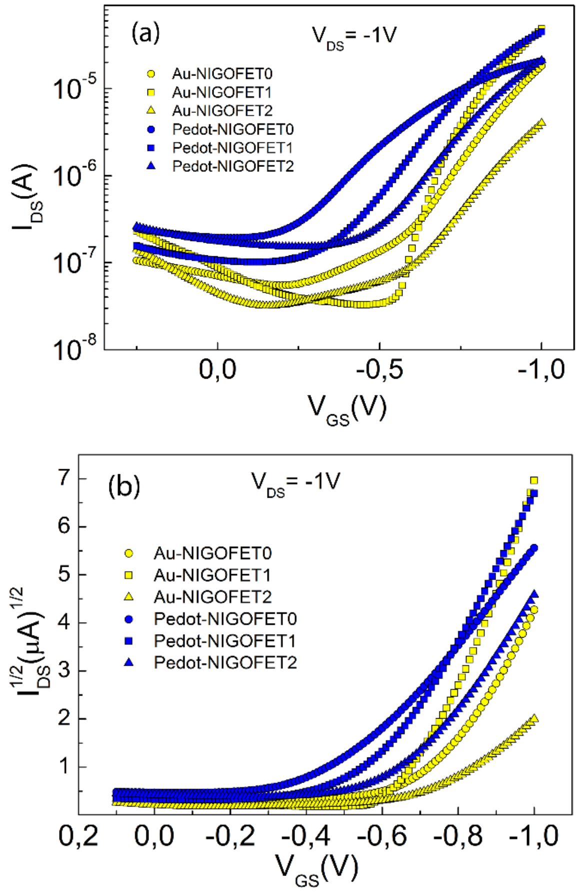

Fig. 4. (a) Transfer characteristics and (b) $I_{DS}^{1/2}$-V_{GS} curve for both Au and Pedot-NIGOFETs

TABLE 1.

COMPARISON OF THE ELECTRICAL PARAMETER OF NIGOFETS WITH AU AND PEDOT:PSS GATE ELECTRODES

NIGOFET	Mobility (μ_{sat}) (cm^2/V.s) @ (V_{GS} = -1V)		V_{TH} (V) @ (V_{DS} = -1V)		I_{ON}/I_{OFF} @ (Vds = -1V)		SS (mV/decade) @ (V_{DS} = -1V)	
	Pedot	**Au**	**Pedot**	**Au**	**Pedot**	**Au**	**Pedot**	**Au**
NIGOFET0	0.010	0.233	-0.500	-0.750	1.1 x 10^2	3.31 x 10^2	290	200
NIGOFET1	0.086	1.720	-0.600	-0.700	4.35 x 10^2	1.43 x 10^3	210	90
NIGOFET2	0.240	1.090	-0.650	-0.800	1.35 x 10^2	1.25 x 10^2	330	230

IV. CONCLUSION

Investigating the effects of different gate electrode materials on top-gate bottom contact NIGOFETs via comparison of the performance of the Au and Pedot-NIGOFETs shows that gate electrodes significantly affect the main electrical parameters of the OFETs. In this respect, the importance of WF and ρ is understood by monitoring and discussing the transfer and output characteristics of the transistors. Initially, the impact of WF only on I_{DS} is isolated and seen that alongside I_{DS}, mobility could be increased by using the Au gate electrode thanks to its higher-WF leading to the formation of fewer injection barriers for holes. However, Au-NIGOFETs have a further negative V_{TH} since the lower-ρ property of Au causes denser charge carrier traps formation along with more charge carrier induction in the NIGD/P3HT interface, which prevents the devices responding to V_{GS} too quickly when the V_{GS} lags behind the V_{TH}. The same mechanism is responsible for the lower I_{OFF} of the Au-NIGOFETs as well. On the other hand, lower-ρ also gives the advantage of abrupt response to the Au-NIGOFET1 when the V_{GS} exceeds the V_{TH}. This allows to the Au-NIGOFET1 having highest I_{ON}/I_{OFF} and lowest SS, which is generally desired in OFET applications. Consequently, it can be said that since NIGD1 is the most qualified dielectric among NIGDs and Au gate electrode is the better option for performance enhancement, Au-NIGOFET1 displays excellent performance, which can be manipulated in electronic applications such as inverter and oscillator.

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REFERENCES

[1] J. Lee, M. J. Panzer, Y. He, T. P. Lodge, and C. D. Frisbie, “Ion Gel Gated Polymer Thin-Film Transistors,” J. Am. Chem. Soc., vol. 129, no. 15, pp. 4532–4533, Apr. 2007. https://doi.org/10.1021/ja070875e

[2] F. Zare Bidoky and C. D. Frisbie, “Parasitic Capacitance Effect on Dynamic Performance of Aerosol-Jet-Printed Sub 2 V Poly(3-hexylthiophene) Electrolyte-Gated Transistors,” ACS Appl. Mater. Interfaces, vol. 8, no. 40, pp. 27012–27017, Oct. 2016. https://doi.org/10.1021/acsami.6b08396

[3] M. J. Panzer and C. D. Frisbie, “Exploiting Ionic Coupling in Electronic Devices: Electrolyte-Gated Organic Field-Effect Transistors,” Adv. Mater., vol. 20, no. 16, pp. 3177–3180, Aug. 2008. https://doi.org/10.1002/adma.200800617

[4] S. Ono, K. Miwa, S. Seki, and J. Takeya, “A comparative study of organic single-crystal transistors gated with various ionic-liquid electrolytes,” Appl. Phys. Lett., vol. 94, no. 6, p. 063301, Feb. 2009. https://doi.org/10.1063/1.3079401

[5] B. Yaman, I. Terkesli, K. M. Turksoy, A. Sanyal, and S. Mutlu, “Fabrication of a planar water gated organic field effect transistor using a hydrophilic polythiophene for improved digital inverter performance,” Org. Electron. physics, Mater. Appl., vol. 15, no. 3, pp. 646–653, Mar. 2014. https://doi.org/10.1016/j.orgel.2013.12.024

[6] T. Yardım, A. Demir, S. Allı, A. Allı, A. Kösemen, and A. G. Yüceda, “Comparison of Electronic Parameters of Low Voltage Organic Field-Effect Transistors with Novel Gel

Gate Insulators," J. Nanoelectron. Optoelectron., vol. 14, no. 6, pp. 833–838, May 2019. https://doi.org/10.1166/jno.2019.2541

[7] Z. Alpaslan Kösemen, A. Kösemen, S. Öztürk, B. Canımkurbey, and Y. Yerlİ, "High mobility and low operation voltage organic field effect transistors by using polymer-gel dielectric and molecular doping," Mater. Sci. Semicond. Process., vol. 66, pp. 207–211, Aug. 2017. https://doi.org/10.1016/j.mssp.2017.04.029

[8] B. Şengez et al., "Use of side chain thiophene containing copolymer as a non-ionic gel-dielectric material for sandwich OFET assembly," Microelectron. Eng., vol. 103, pp. 111–117, Mar. 2013. https://doi.org/10.1016/j.mee.2012.08.014

[9] T. Yardım, İ. Yücedağ, S. Allı, A. Allı, A. Demir, and A. Kösemen, "Comparative investigation of electronic parameters of low voltage organic field-effect transistors with variable capacitance non-ionic gel gate dielectrics," Microelectron. Eng., vol. 215, 2019. https://doi.org/10.1016/j.mee.2019.110981

[10] A. Kösemen et al., "A novel field effect transistor with dielectric polymer gel," Microelectron. Eng., vol. 88, no. 1, pp. 17–20, Jan. 2011. https://doi.org/10.1016/j.mee.2010.08.004

[11] F. Leonardi, A. Tamayo, S. Casalini, and M. Mas-Torrent, "Modification of the gate electrode by self-assembled monolayers in flexible electrolyte-gated organic field effect transistors: Work function: Vs. capacitance effects," RSC Adv., vol. 8, no. 48, pp. 27509–27515, Aug. 2018. https://doi.org/10.1039/C8RA05300F

[12] S. Fabiano, S. Braun, M. Fahlman, X. Crispin, and M. Berggren, "Effect of Gate Electrode Work-Function on Source Charge Injection in Electrolyte-Gated Organic Field-Effect Transistors," Adv. Funct. Mater., vol. 24, no. 5, pp. 695–700, Feb. 2014. https://doi.org/10.1002/adfm.201302070

[13] I. Nausieda, K. K. Ryu, D. Da He, A. I. Akinwande, V. Bulović, and C. G. Sodini, "Dual threshold voltage organic thin-film transistor technology," IEEE Trans. Electron Devices, vol. 57, no. 11, pp. 3027–3032, Nov. 2010. https://doi.org/10.1109/TED.2010.2072550

[14] L. Kergoat et al., "Tuning the threshold voltage in electrolyte-gated organic field-effect transistors," Proc. Natl. Acad. Sci. U. S. A., vol. 109, no. 22, pp. 8394–8399, May 2012. https://doi.org/10.1073/pnas.1120311109

[15] Y. Zhou, H. Cheun, S. Choi, C. Fuentes-Hernandez, and B. Kippelen, "Optimization of a polymer top electrode for inverted semitransparent organic solar cells," Org. Electron. physics, Mater. Appl., vol. 12, no. 5, pp. 827–831, May 2011. https://doi.org/10.1016/j.orgel.2011.02.017

[16] H. Jia, G. K. Pant, E. K. Gross, R. M. Wallace, and B. E. Gnade, "Gate induced leakage and drain current offset in organic thin film transistors," Org. Electron., vol. 7, no. 1, pp. 16–21, 2006. https://doi.org/10.1016/j.orgel.2005.10.003

[17] I. Kymissis, Organic Field Effect Transistors: Theory, Fabrication and Characterization - Ioannis Kymissis - Google Books. 2009. 10.1007/978-0-387-92134-1

[18] W. M. H. Sachtler, G. J. H. Dorgelo, and A. A. Holscher, "The work function of gold," Surf. Sci., vol. 5, no. 2, pp. 221–229, Oct. 1966. https://doi.org/10.1016/0039-6028(66)90083-5

[19] "PEDOT:PSS | PH 1000, Al 4083, HTL Solar & HTL Solar 3 | Ossila." [Online]. Available: https://www.ossila.com/products/pedot-pss?variant=30366225236064. [Accessed: 18-Nov-2019].

[20] S. I. Na et al., "Evolution of nanomorphology and anisotropic conductivity in solvent-modified PEDOT:PSS films for polymeric anodes of polymer solar cells," J. Mater. Chem., vol. 19, no. 47, pp. 9045–9053, 2009. https://doi.org/10.1039/B915756E

[21] L. Xiang, W. Wang, and F. Gao, "Improving Mobility and Stability of Organic Field-Effect Transistors by Employing a Tetratetracontane Modifying PMMA Dielectric," IEEE Trans. Electron Devices, vol. 63, no. 11, pp. 4440–4444, Nov. 2016. 10.1109/TED.2016.2612662

[22] L. Zhang, D. Yang, S. Yang, and B. Zou, "Solution-processed P3HT-based photodetector with field-effect transistor configuration," Appl. Phys. A Mater. Sci. Process., vol. 116, no. 3, pp. 1511–1516, 2014. https://doi.org/10.1007/s00339-014-8280-z

[23] G. Horowitz, R. Hajlaoui, H. Bouchriha, R. Bourguiga, and M. Hajlaoui, "The Concept of 'Threshold Voltage' in Organic Field-Effect Transistors," Adv. Mater., vol. 10, no. 12, pp. 923–927, Aug. 1998. https://doi.org/10.1002/(SICI)1521-4095(199808)10:12<923::AID-ADMA923>3.0.CO;2-W

[24] G. Fortunato and P. Migliorato, "Model for the above-threshold characteristics and threshold voltage in polycrystalline silicon transistors," J. Appl. Phys., vol. 68, no. 5, pp. 2463–2467, 1990.https://doi.org/10.1063/1.346507

[25] D. Braga and G. Horowitz, “Subthreshold regime in rubrene single-crystal organic transistors,” Appl. Phys. A Mater. Sci. Process., vol. 95, no. 1, pp. 193–201, Apr. 2009. https://doi.org/10.1007/s00339-008-5008-y

[26] J. R. Sambles, K. C. Elsom, and D. J. Jarvis, “The Electrical Resistivity of Gold Films,” Philos. Trans. R. Soc. A Math. Phys. Eng. Sci., vol. 304, no. 1486, pp. 365–396, Mar. 1982. https://doi.org/10.1098/rsta.1982.0016

[27] O. Günaydın, A. Demir, A. Atahan, T. Yardım, and İ. Yücedağ, “Evaluation of novel thiophene branched polystyrene as insulator layer in organic electronic device,” J. Mol. Struct., vol. 1185, 2019. https://doi.org/10.1016/j.molstruc.2019.02.097

[28] R. P. Ortiz, A. Facchetti, and T. J. Marks, “High- k Organic, Inorganic, and Hybrid Dielectrics for Low-Voltage Organic Field-Effect Transistors,” Chem. Rev., vol. 110, no. 1, pp. 205–239, Jan. 2010. https://doi.org/10.1021/cr9001275