

Orange dye based field effect transistor as humidity sensor

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In this study aqueous solution of organic semiconductor orange dye (8 wt.%) and sugar (8 wt.%), was prepared. The samples having structure of field effect transistor were fabricated by drop-casting of the solution on the surface-type interdigitated silver electrodes, deposited on ceramic alumina sheet. As a result, sol-gel elastic films of orange dye-sugar blend were fabricated. Drain-source volt-ampere characteristics were slightly non-linear and depend both on humidity level and applied gate-source terminal voltage. The fabricated transistors can be used as humidity sensors.

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1. Introduction

Humidity sensors are used widely in automatic control systems. Majority of the humidity sensors are based on electrical properties of the materials. Three groups of humidity sensors were developed by using electrolytes, organic polymers and porous ceramics [1]. In the last years, field effect transistor (FET) based humidity sensors were fabricated as well [2]. Chen and Lu presented review of materials and mechanisms for different kinds of humidity sensors [3]. In particular, they discussed sensors on the base of ceramics, semiconductors and polymers for measurement of both of relative and absolute humidity which were used in the industry. It was investigated and presented data on the sensitivity, response time and stability of the sensors, including sensors based on Al₂O₃. The composites of iron oxide and polypyrrole were used for humidity and gas sensing purposes [4]. As concentration of polypyrrole was increased, the sensitivity of the sensors was increased as well. Gas sensing properties of the sensors were investigated for CO₂, N₂ and CH₄. Recent development in miniaturized humidity sensors was presented in Ref. [5]. In particular, capacitive, hydrometric, gravimetric, optical and integrated humidity sensors were discussed.

In past years, a number of papers were published on humidity sensors based on organic semiconductors and composites. A humidity sensing organic-inorganic composite for environmental monitoring was investigated in Ref. [6]. A number of resistive humidity sensors were designed, fabricated and investigated, based on vanadium complex (VO₂(3-fl)) films [7]. Orange dye (OD) and CNT based humidity sensors were fabricated by high gravity thin film deposition technique [8]. Effect of humidity was investigated on NiPc based organic photo field effect transistor [9]. Fabrication and investigation of cellulose

acetate-copper oxide nano-composite based humidity sensors were presented in Ref. [10]. Impact of moisture contents on the performance of organic bi-layer ITO/OD thermoelectric cell was observed by Ahmad *et al.* [11].

Present study is continuation of our efforts for the investigation of humidity sensors and organic semiconductors where we are presenting the properties of the orange dye based field effect transistor which can be used as humidity sensor.

2. Experimental

In this study, an aqueous solution of commercially available organic semiconductor orange dye (8 wt.%) and sugar (8 wt.%) was prepared. As orange dye (OD) and sugar (disaccharides) both are dissolved in water well, we can assume that these both ingredients blend solution will form here some complex. Fig. 1 shows molecular structure of orange dye [8] and Fig. 2 represent molecular structure of sugar. The sugar was used for fabrication of conducting coating [12]. It was observed by us that sugar make adhesion of the deposited film much better than that of only OD films deposited from aqueous solution. As a solvent distilled water was used. Commercially available surface-type interdigitated silver electrodes coated with ceramic alumina sheet, fabricated by screen printing and chemical etching technology were used as the substrates [8]. Sizes of substrate were 14 mm × 7 mm, with 0.5mm width of electrodes and interelectrode distances as well of 200 μm. Length of the electrodes was equal to 7mm.

The samples were fabricated by drop-casting of the solution. Fig. 3 shows atomic force microscope (AFM) image of the OD-sugar sample. A very high level of roughness of the sample surface is observed. Fig. 4 shows cross section of the OFET.

The thickness of the OD-sugar thin films were in the range of 810–930 nm. The OD-sugar samples were deposited by drop-casting on flexible dielectric substrates as well and it was found that OD-sugar films are actually gel, showing good flexibility and softness. This technology is called sol-gel technology which before was developed and used for fabrication of silicate thin films on silicon [13]. By using thermoelectric (Seebeck) effect, it was found that the OD-sugar samples were p-type semiconductors.

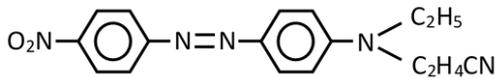


Fig. 1. Molecular structure of orange dye (OD)

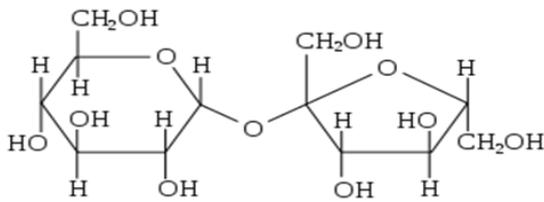


Fig. 2. Molecular structure of sugar

For measurements of voltage and current, digital multimeters HIOKI DT4252 and HIOKI DT4253 were used. Experiments were conducted at room temperature conditions.

3. Results and discussions

Fig. 5 shows drain-source voltage (V_{DS}) – drain-source current (I_{DS}) relationships for the OD-sugar humidity sensor at 56%, 60% and 70% RH levels. It is seen that with increase of humidity current increases at the constant voltage. This relationship can be converted to dependence of resistance of the sample on humidity level (Fig. 6), which show sharp decrease of the resistance at $V_{DS} = 7$ V with increase of humidity. Resistive (S_R) and current (S_I) sensitivities of the sensor were estimated by the following expressions:

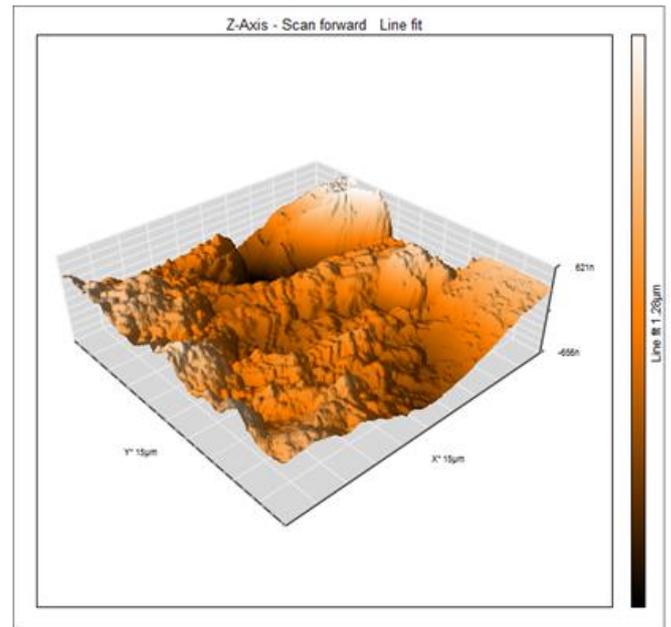
$$S_R = \frac{\Delta R}{R(\Delta RH)} \quad (1)$$

$$S_I = \frac{\Delta I}{I(\Delta RH)} \quad (2)$$

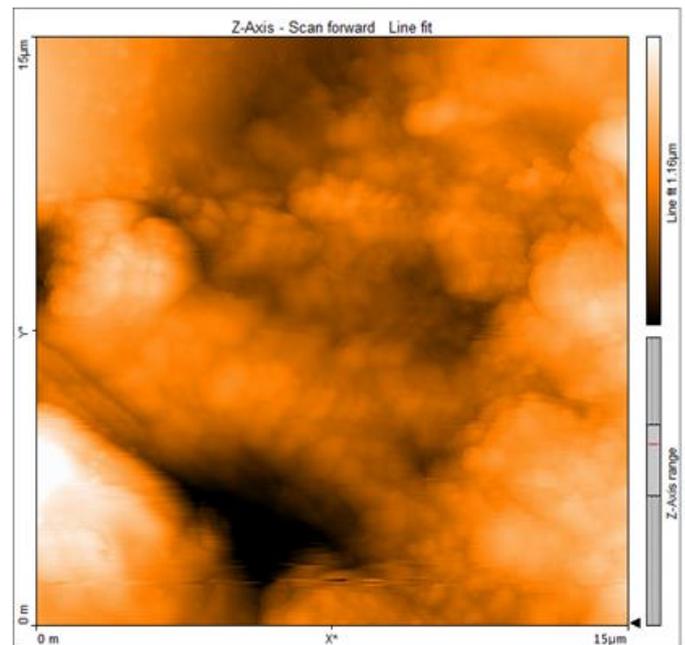
where ΔR , R and ΔRH are change of the resistance, resistance and change of the relative humidity, ΔI and I change of current and value of current. It was calculated

that average relative resistive and current sensitivities were equal to -5.7% and +5.7% per unit of relative humidity.

Response and recovery times were equal to 11 s and 32 s accordingly for a humidity change from 50% to 90% RH.



a)



b)

Fig. 3. Atomic force microscope image of the OD-sugar film: 3D (a) and 2D (b) images (color online)

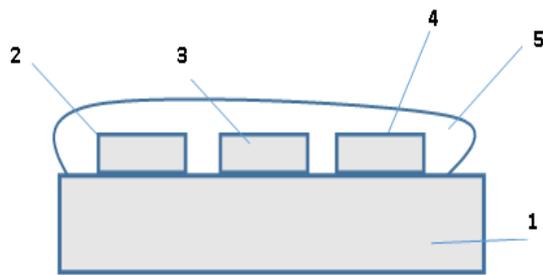


Fig. 4. Cross section of OD-Sugar based OFET: ceramic substrate (1), source (2), gate (3), drain (4), orange dye complex film (5)

Humidity effect on electrical properties of organic thin film transistors was investigated by Dawen *et al.* [14] and it was observed that output current and mobility decreased as relative humidity was increased. It was attributed to charge trapping by polar water molecules reducing the rate of charge transport. In metal oxides (ceramics), it was classified two types of conduction: ionic and electronic types [15]. In the first type, it was considered the presence of ionic (H^+) conductivity due to capillary condensation of water vapor. In the second type of materials, water molecules played the role of electron donating gas and conductivity may be increased or decreased depending on the n or p-type nature of semiconductor.

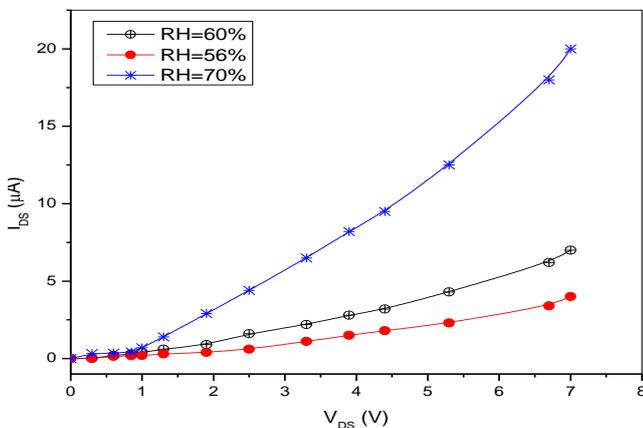


Fig. 5. Atomic Drain-source voltage (V_{DS}) – drain-source current (I_{DS}) relationships for the OD-sugar humidity sensor at different humidity 56%, 60% and 70% (color online)

Generally speaking, several humidity sensing mechanisms have been proposed and studied. In particular, sensing may be due to ionic, proton, conduction of water molecules, electronic, solid-electrolyte and capacitive type conduction, chemical adsorption, physical adsorption and capillary condensation processes [16].

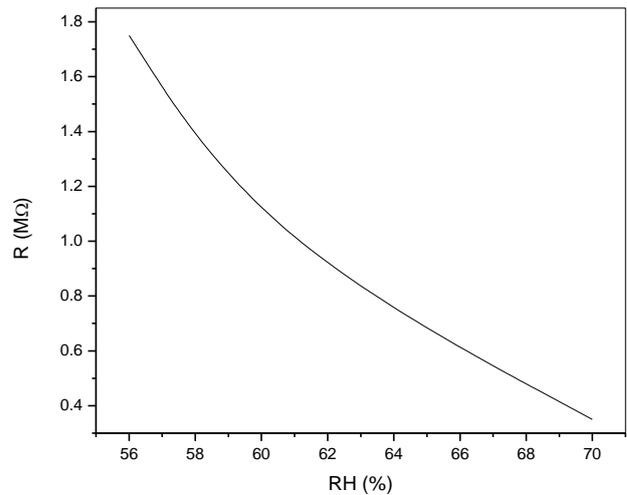


Fig. 6. Dependence of resistance of the OD-sugar sensor on the humidity

In our case, OD and sugar as well are dissolved well in water. Therefore, it can be assumed that along with proton conductivity of H^+ due to donor-acceptor charge transfer, electronic conductivity take place in organic semiconductors which bring an increase of concentration and accordingly total conductivity. On the other hand, as Fig. 5 shows, drain-source voltage (V_{DS})–drain-source current (I_{DS}) relationships are actually non-linear. It may be considered that metal-semiconductor Schottky junctions with depletion region, are present in the Ag-OD-Ag structures, as shown in Fig. 7. From electronic point of view, these junctions can be represented as oppositely connected semiconductor diodes as shown in Fig. 8 as equivalent circuit. Presence of depletion region definitely influence to the sensitivity of the device positively.

Fig. 9 shows I_{DS} – V_{DS} relationships for the OFET, based on OD-sugar at different V_{GS} voltage. These characteristics are similar to the characteristics shown in Fig. 5. I_{DS} – V_{GS} relationship for the OFET at $V_{DS} = 7$ V are presented in Fig. 10. It is seen that the operation of the investigated OFET is enhancement type which is well described as for traditional inorganic FETs [17]. It should be mentioned that in standard thin film OFETs, source and drain terminals are placed on one plane, but gate terminal in opposite plane [18]. In organic single crystal FETs, all terminals are put in one plane, in the top of crystal [18]. In our case (Fig. 4), all terminals are in the bottom plane. This structure is easier to fabricate and potentially more efficient, especially for sensor application of the OFETs, because no top electrode which could interfere to the diffusion of gas or humid to the conductive channel of the transistor.

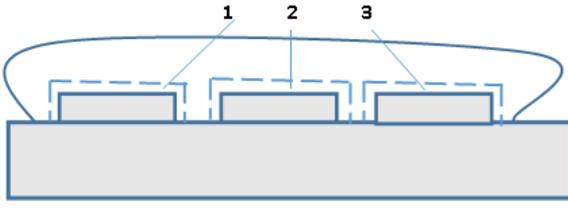


Fig. 7. Cross section of OFET: depletion regions in source (1), gate (2) and drain (3)



Fig. 8. Equivalent circuit of two semiconductor diodes connected in opposite

As is known, drain current of the field effect transistors depends on conduction channel width (W) and length (L) (Eq. 2 and Eq. 3) [19]:

$$I_{DS, \text{sat}} = \frac{\mu WC(V_{GS} - V_t)^2}{2L} \quad (3)$$

$$I_{DS, \text{lin}} = \frac{\mu WC(V_{GS} - V_t)}{L} \quad (4)$$

where $I_{DS, \text{sat}}$ and $I_{DS, \text{lin}}$ drain-source saturation and drain-source linear characteristics currents, μ is mobility, C is capacitance of gap, V_{GS} , V_t and V_{DS} gate-source, threshold and drain-source voltages. It should be mention that in these transistors, only non-linear or quasi-linear behavior of drain-source current dependence on drain-source voltage was observed (Fig. 5).

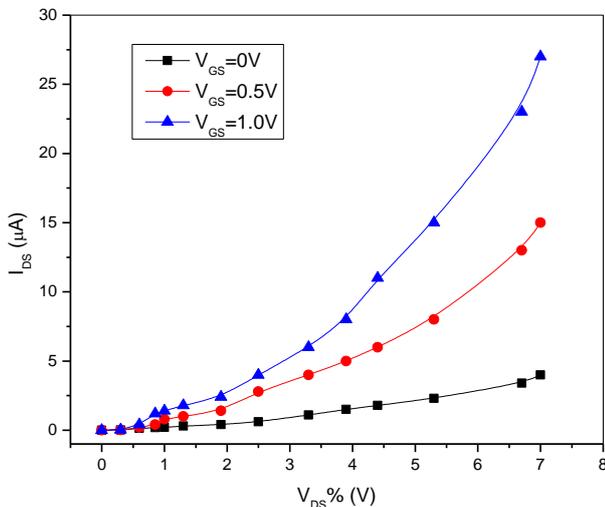


Fig. 9. I_{DS} - V_{DS} relationships for the OD-Sugar based OFET based at different V_{GS} : (i) 0 V; (ii) 0.5 V and (iii) 1.0 V (color online)

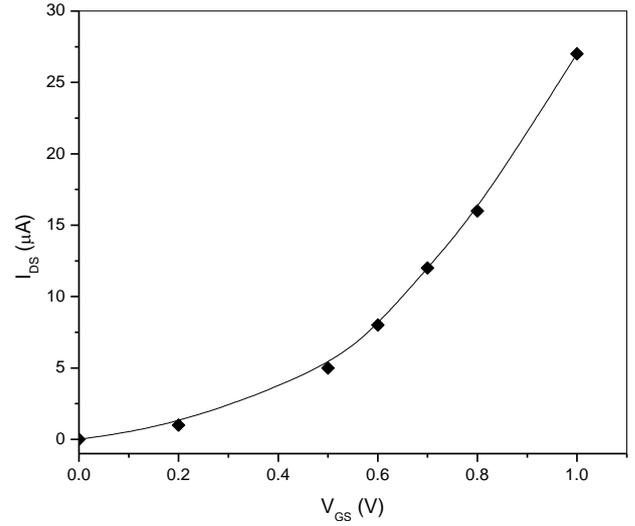


Fig. 10. I_{DS} - V_{GS} relationships for the OD-sugar based OFET at $V_{DS} = 7$ V

Sensitivity of the OFETs can be determined by transconductance (g_m):

$$g_m = \frac{\partial I_D}{\partial V_{GS}} \quad (5)$$

which actually depends upon the change in the resistance of the channel or accordingly volume of depletion region, under the effect of applied input voltage or, in our case, humidity, or temperature, pressure or some kind of input parameter, in general case. Unlike to well-known structures of FETs, in the present case of fabricated and investigated FETs, depletion region is available around of all terminals (Fig. 7), not only or mostly of gate terminal as in conventional FETs [17,18]. This structure (Fig. 4 and Fig. 7) potentially allows to fabricate sensitive devices for practical application despite of larger interterminal distances and terminals sizes.

Traditional semiconductor-metal ohmic or rectifying Schottky contacts are not limit all variety of metal-semiconductor contacts. Recently, contact resistances between organic semiconductors poly (3-hexylthiophene) and metal electrodes in organic field effect transistor was investigated [20]. It was observed that the contact resistances play a dominant role in electronic charge injection properties in organic field effect transistors. Therefore, it was assumed that this effect should not be ignored when examining intrinsic properties such as the mobility and its dependence on temperature or gate voltage for both ohmic and nonlinear charge injection. It is an important step toward improved understanding and modeling of these devices.

4. Conclusion

It was fabricated and investigated the properties of orange dye and sugar complex sol-gel based field effect

transistor. All terminals, source, gate and drain of the transistor were placed in the bottom plane unlike to traditional configurations. Response and recovery times were equal to 11s and 32s accordingly for a change of humidity from 50% to 90% RH. It was shown that transistor is sensitive to humidity. The fabricated FET can be used as humidity sensor and for demonstration purposes in education.

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