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OFET MICRO AND MACRO CONDUCTIVITY

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Abstract In this paper, after specifying the basic electronic features of OFET (Organic Field Effect Transistor), the conductivity of such transistor is considered. Going down to the micro level, an expression for the conductivity is given, and then the total conductivity is considered and determined. New limits of integration have been proposed. A correction factor is also introduced.

Keywords: Organic field effect transistor (OFET); conductivity.

1. INTRODUCTION

The standard and most commonly used materials for the production of transistors are of inorganic origin. This is the fact since the beginning of the production of these devices. For the realization of active parts of the electronic component silicon is most used up to now, but other materials are also used, such as Ge, GaAs, SiC, heterostructures etc.

The idea of using organic material to make active part of an electronic component appeared only a few years after the realization of classic - inorganic-based components. However, considering the success of Si-based transistors, organic based transistors considerations remained theoretical for many years, without practical realizations. In the sixties of the twentieth century, they began to be used in photoconductive components - specifically in copiers and printers.

Today, the industry of products using organic transistors has an annual profit of several billion dollars.

As for the electron device itself, the idea is to use organic materials that have semiconductor properties. Semiconductivity, in this type of material, occurs in molecules and in chains of molecules.

2. ORGANIC FIELD EFFECT TRANSISTOR (OFET) - ADVANTAGES, DISADVANTAGES AND POSSIBLE APPLICATIONS

Organic Field Effect Transistors (OFET), like other transistors, can be used as amplifier component or as switch component.

The good properties of organic-based transistors are numerous. The production of these transistors is relatively cheap, thus OFETs are low cost components. OFETs are flexible, which enables significant applications in practice. They easily adapt to surfaces. They save space. Devices made of organic materials are light, which is again suitable for the realization of various applications. They are practically unbreakable. Their production is not harmful to the environment. Significant OFET characteristics is that this type of transistor has a high degree of compatibility with inorganic-based devices.

The disadvantage is the low electrical conductivity, which limits the use of this type of transistor in some applications. The development of new polymers, in which the characteristics related to conductivity will be improved, require a lot of time and financial resources. Also, it is not known with certainty what the possibilities of long-period use of these devices are.

Some of the possibilities for the application of this type of transistor should be kept in mind. OFET can be used to produce flexible displays. Their application is also possible for the production of smart cards, which require great flexibility and a lower density of transistors. Flexible solar cells can be made using these transistors. The same is for making e-paper. OFETs can be used for pharmaceutical purposes, considering that organic materials react to biological and chemical changes.

The prospects for using OFETs are great. For instance, transparent films with photocells, which would be placed on mobile devices - e.g. to mobile phones, computers, which provide additional energy for the device, and thus significantly increase the life of the battery. Such transparent foils could also be stuck on window panes, which would provide clean energy (and the energy thus obtained, can be used inside room).

3. OFET STRUCTURE

In comparsion with the standard, inorganic MOSFETs (Metal Oxide Semiconducor Field Effec Transistors), OFET has organic based active layer. All transport processes take place in this area. In other words, OFET current is current that flows in organic based area. Other layers just „support“ organic based semiconductor layer in which channel is formed [1-12].

The OFET (geometric) structure can be different. The structure of a transistor has an impact on the characteristics of a transistor itself. Different layers and electrodes position also determine the characteristics of a transistor. This can be used to provide desired transistor features.

Some possible cross sectional views of OFETs, with different structure, are shown in figures 1.a. and 1.b.

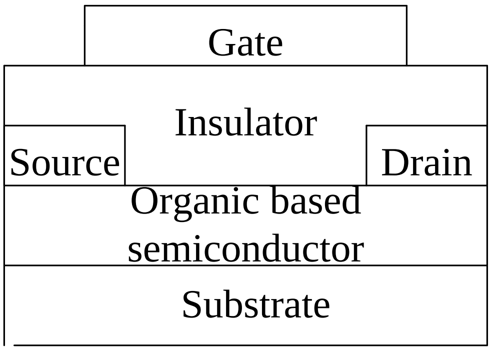

Figure 1.a. OFET with top gate position (like in standard MOSFET realisation).

In figure 1.a, cross sectional view of OFET with electrodes positions like in standard MOSFET is presented. Source and drain electrodes are placed on organic semiconductor layer – active area. Gate electrode is on the top, devided by dielectric (insulator layer) from active area.

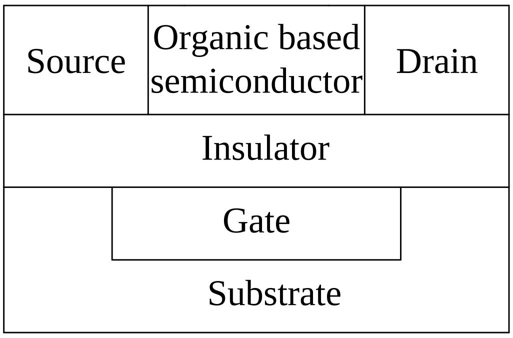

Figure 1.b. OFET with bottom gate position and organic layer between source and drain electrode.

In figure 1.b, cross sectional view of OFET with organic semiconductor layer – active area, placed between source and drain electrodes, is shown. Gate electrode is on the bottom, devided by dielectric (insulator layer) from active area. All structure is growth on substrate.

OFET layers can be very thin. The order of magnitude of layer thickness can be a few tens to several hundred nanometers. Such transistors are called Thin Film Transistors (TFT). Gate thicknes can be 10nm, while source and drain thicknes can be 60nm.

4. OFET CONDUCTIVITY

It has already been said that the main disadvantage of OFETs is the low level of carriers concentration in the active area of the device. Consequently, conductivity of these transistors is low.

Well known and standard model for the conductivity is (by definition):

$$\sigma = Q \cdot n \cdot \mu_n + Q \cdot p \cdot \mu_p \quad (1)$$

where Q is the electron charge, μn is the electron mobility, μp is the hole mobility, n is the concentration of electrons and p is the concentration of holes. In the case of doped materials, the imapct of one type (minority type) of charge carriers can be neglected. The same is for an elcetron-only device. Thus, a simple connection between conductivity and carriers mobility is:

$$\sigma = Q \cdot n \cdot \mu \quad (2)$$

The induced charges, in the active area, can be calculated as:

$$Q_{ind} = C_{ins} \cdot \left(V_{GS} - \frac{V_{DS}}{2} - V_T \right) \quad (3)$$

where C_{ox} is the capacitance of the insulator, V_{GS} is the gate to source voltage, V_{DS} is the drain to source voltage, V_T is the threshold voltage. And previous, well known equaton gives the average carriers concentration n_{av}, in the OFETs active layer [e.g. 2, 12].

Getting down to the micro-level, the carrier concentration in the active, organic layer, can be obtained from:

$$n(E) = \frac{\vartheta\cdot(\beta_{bds})^{\alpha}}{(E_i-E_j)\cdot\sqrt{2\pi}}\cdot e^{\frac{-\left(E-\frac{E_i+E_j}{2}\right)}{2\cdot\left(E_i-E_j\right)^2}} \tag{4}$$

where β_{bds} is the characteristic band density of states (e. g. $2\cdot10^{21}$cm^{-3}), and E_i, E_j is are energy levels, υ is the correction factor, α is the proposed coefficient whose value is in the range of 1.07 and 1.25.

Introducing the Fermi-Dirac distribution, for a sample that is at a low temperture, it holds that:

$$f(E,T) = \frac{1}{1+e^{\frac{E-E_F}{kT}}} \sim e^{\frac{-(E-E_F)}{kT}} \tag{5}$$

where E is the fermion energy on the temperature T, E_F is the Fermi energy and k is the Boltzmann´s constant.

The summary carrier concentration can be calculated as:

$$n_{summary}(T) = \int_{LLI}^{ULI} n(E)\cdot f(E,T)\cdot dE \tag{6}$$

or:

$$n_{summary}(T) = \int\limits_{LLI}^{ULI} \frac{\vartheta\cdot(\beta_{bds})^{\alpha}}{(E_i-E_j)\cdot\sqrt{2\pi}}\cdot e^{\frac{-\left(E-\frac{E_i+E_j}{2}\right)}{2\cdot\left(E_i-E_j\right)^2}}\cdot e^{\frac{-(E-E_F)}{kT}}\cdot dE$$

where LLI is the lover limit of interest and ULI is the upper limit of interest. By introducing certain limits of integration, a better and easier physical interpretation of this mathematical model is ensured.

The dependence of microscopic conductivity on energy, can be expressed as [3, 4]:

$$\sigma(E) = Q^2\cdot n(E)\cdot D(E) \tag{7}$$

where $D(E)$ is the diffusivity dependence on energy (for each energy).

The rate of change of the Fermi function affects the electrical conductivity to be higher or lower, in other words the conductivity depends on the gradient of the Fermi function. Using the Kubo-Greenwood integral similar to [3, 4], the summary conductivity can be calculated:

$$\sigma_{summary}(T) = \int_{LLI}^{ULI} \sigma(E) \cdot \left(-\frac{\partial f(E,T)}{\partial E}\right) \cdot dE \tag{8}$$

or:

$$\sigma_{summary}(T) = \frac{Q^2}{kT} \int_{LLI}^{ULI} \cdot \frac{\vartheta \cdot (\beta_{bds})^{\alpha}}{(E_i - E_j) \cdot \sqrt{2\pi}} \cdot e^{\frac{-\left(E - \frac{E_i + E_j}{2}\right)}{2 \cdot (E_i - E_j)^2}} \cdot D(E) \cdot \left(e^{\frac{-(E - E_F)}{kT}}\right) \cdot dE$$

The effective mobility is than:

$$\mu_{eff}(T) = \frac{\sigma_{summary}(T)}{Q \cdot n_{summary}(T)} = \frac{\int_{LLI}^{ULI} \sigma(E) \cdot \left(-\frac{\partial f(E,T)}{\partial E}\right) \cdot dE}{\int_{LLI}^{ULI} n(E) \cdot f(E,T) \cdot dE}$$

or:

$$\mu_{eff}(T) = \frac{\frac{Q^2}{kT} \int_{LLI}^{ULI} \frac{\vartheta \cdot (\beta_{bds})^{\alpha}}{(E_i - E_j) \cdot \sqrt{2\pi}} \cdot e^{\frac{-\left(E - \frac{E_i + E_j}{2}\right)}{2 \cdot (E_i - E_j)^2}} \cdot D(E) \cdot \left(e^{\frac{-(E - E_F)}{kT}}\right) \cdot dE}{Q \cdot \int_{LLI}^{ULI} \frac{\vartheta \cdot (\beta_{bds})^{\alpha}}{(E_i - E_j) \cdot \sqrt{2\pi}} \cdot e^{\frac{-\left(E - \frac{E_i + E_j}{2}\right)}{2 \cdot (E_i - E_j)^2}} \cdot e^{\frac{-(E - E_F)}{kT}} \cdot dE}$$

It should be noted that calculation of the Kubo-Greenwood electrical conductivity has significant challenges [5].

In some applications (models), diffusivity can be assumed as constant value *D* (not energy dependent). In that case, using the last equation, the effective mobilty becomes (well known Einstein relation):

$$\mu_{eff}(T) = \frac{Q}{k \cdot T} \cdot D$$

which verifies the previous considerations.

In Figure 2., OFET conductance dependence on gate-to-source voltage V_{GS}, for different drain-to-source voltage, is presented.

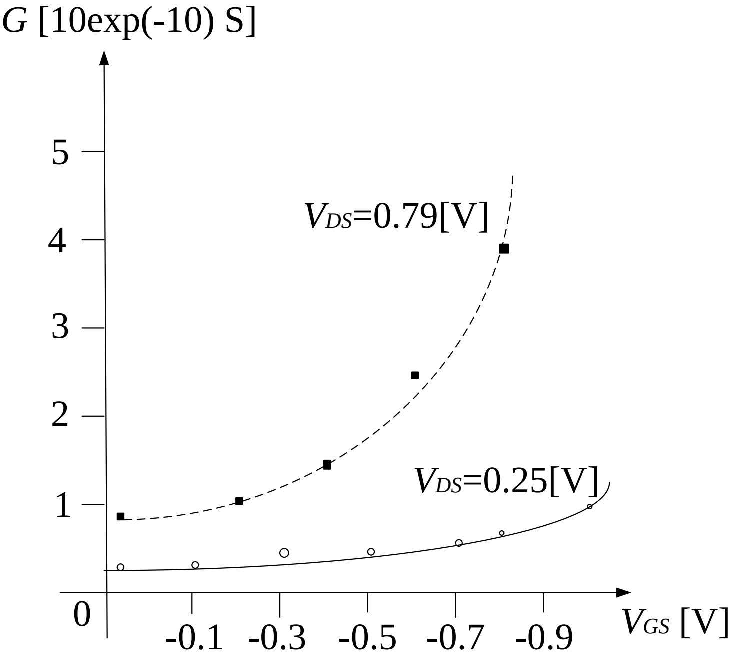

Figure 2. OFET conductance versus gate-to-source voltage, for different drain-to-sorce voltage.

4. CONCLUSIONS

OFET conductivity was discussed and analyzed in the paper. Starting from the micro-conductivity, the macro-conductivity of this transistor was determined with detailed considerations and discussion. The use of appropriate correction factors and coefficients is proposed, in the model for the concentration of charge carriers. New limits of integration are introduced, which ensures greater precision, as well as clearer physical interpretation.

References

[1] Šašić R. M., Lukić P.M., 2007, Conduction Mechanism Based Model of Organic Field Effect Transistor Structure, *Materials Science Forum* (*titled Research Trends in Contemporary Materials Science)*, Vol. 555, pp. 125.-130.

[2] Ramović R, Šašić R., 1999, Analysis and modeling of unipolar small dimension transistors (serbian edition), Dinex, Belgrade.

[3] Xu Y., Benwadih M., Gwoziecki R., et all., 2011, Carrier mobility in organic field-effect transistors, *Journal of Applied Physics,* 110(10), November 2011.

[4] Mott N. F. and Davis E. A., 1979, *Electronic Process in Non-Crystalline Materials*, Clarendon, Oxford.

[5] Calderin L., Karasiev V. V.,. Trickey S. B, 2017, Kubo-Greenwood Electrical Conductivity Formulation and Implementation for Projector Augmented Wawe Datasets, *Computer Physics Communications*, 221, 118–142.

[6] Dodabalapur A., Katz H. E., Torsi L., Haddon R. C., 1995, Organic heterostructure field-effect transistors, *Science*, Vol. 269, pp. 1560-1562.

[7] Dodabalapur A., Torsi L., Katz H. E., 1995, Organic transistors: Two-dimensional transport and improved electrical characteristics, *Science*, Vol. 268, pp. 270-271.

[8] Torsi L., Dodabalapur A., Katz H. E., 1995, An analytical model foor short-channel organic field-effect transistors, *J. Appl. Phys*., Vol. 78, pp. 1088-1093.

[9] Cui T., Liu Y., & Varahramyan K., 2004, Fabrication and Characterization of Polymeric P-Channel Junction FETs, *IEEE Transactions on Electron Devices*, 51(3), 389–393.

[10] Tessler N., Roichman Y., 2001, Two dimensional simulation of polymer field-effect transistors, *J. Appl. Phys*., Vol. 79, No. 18, pp. 2987-2989.

[11] Horowitz G., Delannoy P., 1990, An analytical model for organic-based thin film transistors, *J. Appl. Phys*., Vol. 70, No.1, pp. 469-475.

[12] Boudouris B. W., Organic Electron devices, Purdue University.