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MODELING OF TRAPS CONCENTRATION AND ELECTRIC FIELD DEGRADATION IMPACT ON CARRIERS MOBILITY IN ORGANIC MATERIAL BASED TRANSISTOR

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Abstract: In this paper, new - improved carriers mobility model of OFET (Organic Field Effect Transistor) structures is presented. It is proposed to introduce two new factors: traps concentration ratio and electric field degradation factor, in carriers mobility model. The imact of OFET geometry is also considered. The above-mentioned model includes also carriers mobility dependence on temperature and electric field. Proposed model is incorporated in current-voltage characteristics of OFET.

Keywords: Traps concentration ratio; electric field degradation factor; organic field effect transistor (OFET); carriers mobility model.

1. INTRODUCTION

Electronic devices are incorporated in our daily life (from standard ones, like: mobile phones, tablets, computers, to very special like some medical equipment, car electronic devices, aircraft devices...). From the very begining of the modern Electronics, such devices have been made from inorganic materials – inorganic semiconductors (silicon is most used up to now, but well known materials, for electronic components, are also Ge, GaAs, and modern: SiC, heterostructures etc.).

New materials and new concepts in this area are investigated [1-10]. Very good and promising solution is organic based electronic components.

Research of electronic component is a complex and demanding job (task). Special attention is paid to determing the basic electronic characteristics, which primarily includes current-voltage characteristics. In these characteristics, the carriers mobility has one of the central points. The current conduction mechanism is directly related to carriers mobility.

2. ORGANIC FIELD EFFECT TRANSISTOR

The first Organic Field Effect Transistors (OFETs), was reported in 1986. OFET, like other transistors, can be used as amplifier component or as switch component.

Advantages of organic (over inorganic) electronic components are significant. Thanks to their structure, organic components can be flexible or foldable and are inherently lightweight. The producing procedures are cost effective. These components can be used in wide spectrum of applications. There is high degree of compatibility with standard inorganic components.

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In comparsion with the standard inorganic MOSFETs (Metal Oxide Semiconducor Field Effec Transistors), OFET has organic based semiconductor layer. The central, active area is in this organic based semiconductor. All transport processes are going on in this area. In other words, OFET current is current that flows in mentioned area. Other layers just „support" organic based semiconductor layer in which channel is formed [1, 3-6].

The OFET structure can be different. Some possible cross sectional views of OFETs are presented in Figures 1, 2, 3, 4, 5.

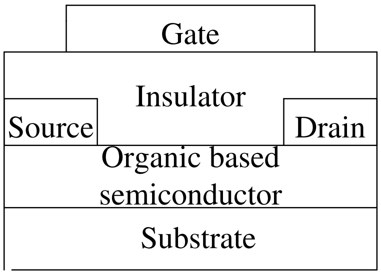

Figure 1. OFET with top gate position (like in standard MOSFET realisation).

In Figure 1, cross sectional view of OFET with electrodes positions like in standard MOSFET is shown. 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.

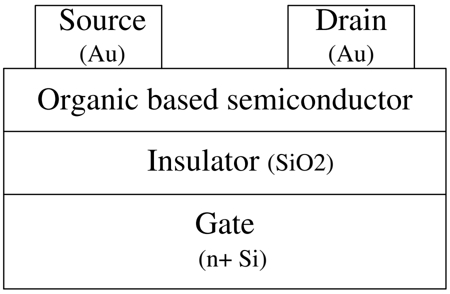

Figure 2. OFET with bottom gate position.

In Figure 2, cross sectional view of OFET with source and drain electrodes placed on organic semiconductor layer – active area, is shown. Gate electrode is on the bottom, devided by dielectric (insulator layer) from the active area.

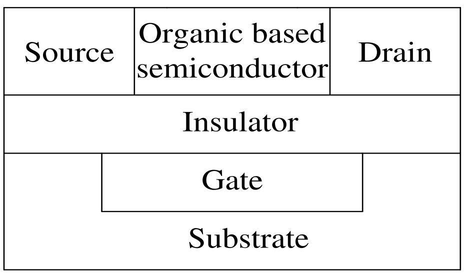

Figure 3. OFET with bottom gate position and organic layer between source and drain electrode.

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In Figure 3, 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.

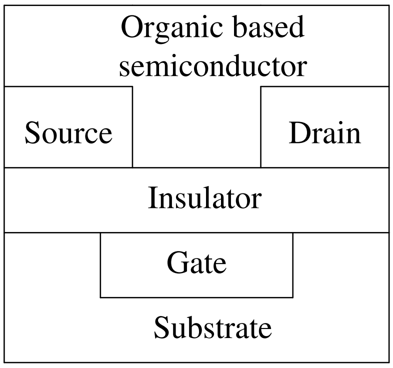

Figure 4. OFET with bottom gate position and organic layer between and above source and drain electrode.

In Figure 4, cross sectional view of OFET with organic semiconductor layer – active area, placed between and above source and drain electrodes, is shown. Gate electrode is on the bottom, devided by dielectric (insulator layer) from the active area. All structure is growth on substrate.

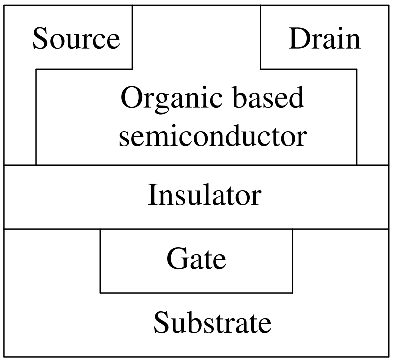

Figure 5. OFET with bottom gate position and active layer between and under source and drain electrode.

In Figure 5, cross sectional view of OFET with organic semiconductor layer – active area, placed between and below source and drain electrodes, is shown. Gate electrode is on the bottom, devided by dielectric (insulator layer) from the 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.

Different layers and electrodes position and different geometry affect the different OFET characteristics. This can be used to provide desired transistor features.

In the paper, transistor shown in the Figure 1. will be primarily considered. However, the factor that takes into account transistors' geometry will also be introduced.

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3. SUGGESTED CARRIERS MOBILITY MODEL

Values of OFET's carriers mobility are much below the corresponding ones in standard semiconductor MOSFETs. This problem was relativelly solved in 1990s [3-6].

In some applications, carriers mobility is considered constant. That approximation sometimes applies. Essentially, it dependes on many parameters and factors., and it is not easy to model it. Different OFET's carriers mobility models have been developed and proposed. All of them are based on the model of multiple grasping (gripping) and releasing of carriers (NITR), made for TFT using amorphous silicon [6].

It is known that carriers mobility depednds on applied electric field and temperature. The investigation of organic materials transport mechanism and mobility is more complex than in semiconductor ones. Doping level must be taken into account, as well as the concentration of traps which causes the carriers scattering.

Starting from the equation proposed in [1] (and models known in the literature [5-7]), in this paper new - improved carriers mobility model is suggested:

$$(E, E_N, T, r_{TD}) = \mu_0 \cdot (r_{TD})^{-1} \cdot \sqrt{1 - \frac{2Q_e \cdot a}{K_p} \cdot E \cdot \left(\frac{E - 0.79E_N}{E}\right)^{\alpha}} \cdot exp\left(\left(\frac{Qe \cdot a \cdot E \cdot \left(\frac{E - 0.79E_N}{E}\right)^{\alpha}}{kT} - \left(\frac{T_0}{T}\right)^2\right)\right) \quad (1)$$

In equation (1), new traps concentration ratio r_{TD} is proposed:

$$r_{TD} = \frac{N_{trap}}{N} \quad (2)$$

If the concentration of molecules is $N \approx 10^{21}\mathrm{cm}^{-3}$ and the traps concentration is $N_{trap} \approx 10^{17}\mathrm{cm}^{-3}$, traps concentration ratio is approximately 10^{-2}. In general, it can have different values, depending on the sample, but previously specified order of magnitude is typical (e.g. it can be 50 or 150, for the assumed concentrations). The modeling and determining of this factor can be considered. It is not simple. First of all, it is practically impossible to make two identical samples. Particularly the question is how to determine trap concentrations in a sample.

In equation (1), the new electric field degradation (correction) factor is introduced:

$$\left(\frac{E - 0.79 \cdot E_N}{E}\right)^{\alpha} \quad (3)$$

The lateral electric field (E) provides carriers movement in the desired direction. Degradation of the lateral electric field is obvious, because the vertical (normal) electric field exists. Vertical (normal) electric field is marked as E_N.

This factor (3) is significantly influenced by the geometry of transistor. Mentioned effect is taken into account through the parameter α. For the structure shown in Figure 1, it can be assumed that α≈1.

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In equation (1), other parameters are: Q_e is the electron charge, a is the hopping distance. It can be assumed a=5nm. The polaron binding energy is $K_p=1.6\cdot 10^{-20}$J. Presented model can be used for the temperature T and electric field E ranges 200–400K and 50–1000kV/cm, respectively.

4. OFET CURRENT-VOLTAGE CHARACTERISTICS WITH PROPOSED CARRIERS MOBILITY MODEL

Proposed carriers mobility model can be used to determine OFET current – voltage characteristics.

Current-voltage characteristics of organic transistors are very similar to those developed in the case of standard, inorganic Si MOSFETs:

For:

$$U_{DS} < U_{DSsat}$$

$$I_{DS} = \mu(E,T,U_{GS}) \cdot \frac{\varepsilon_{ox}}{d_{ox}} \cdot \frac{W}{L} \cdot \left((U_{GS} - U_{th})U_{DS} - \frac{1}{2} \cdot {U_{DS}}^2 \right) \tag{4}$$

For:

$$U_{DS} > U_{DSsat}$$

$$I_{DS} = \frac{\mu(E,T,U_{GS})}{2} \cdot (U_{GS} - U_{th})^2 \tag{5}$$

In equations (4), (5) U_{GS} is the gate to source voltage, U_{th} is the threshold voltage, U_{DS} is the drain to source voltage, d_{ox} is the oxide layer width, W is the channel width and L is the channel length.

By using the proposed models (1), (4), (5), OFET current-voltage characteristics can be determined. It can be valid in the range -80V≤U_{GS}≤0V and -80V≤U_{DS}≤0V. The obtained results are presented in Figure 6.

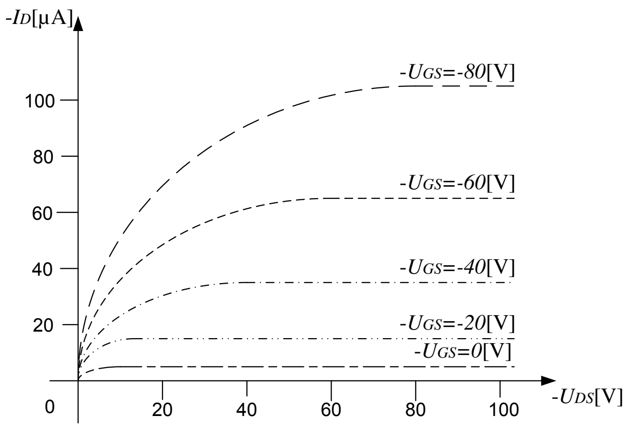

Figure 6. OTFT Current-Voltage characteristic

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The calculations were performed for the following values: channel length L=20nm, channel width W=200nm, temperature T=300K, electric field $E=10^5$V/cm, vertical electric field $E_N=5\cdot10^3$V/cm, α=1, trap density ratio $r_{TD}=10^{-2}$.

It is noted that relatively high voltages provide relatively small currents. A major reason for this phenomenon is low carriers mobility.

5. CONCLUSION

It is very difficult to reproduce structure of organic based thin semiconductor layers. Therefore, the carriers mobility in OFET structures significant varies from one sample to another. If a different geometric structure is taken into account, the problem becomes even more pronounced.

In this paper, the new – improved OFET carriers mobility model is proposed, which takes into account the main characteristics of organic based transistors and therefore it can be widely used.

Two new factors are proposed: traps concentration ratio and electric field degradation factor. Traps concentration ratio specifies traps concentration and impact of that value on carriers mobility. Electric field degradation factor shows and quantifies how the vertical electric field destimulates the carriers movement in the desired direction. The impact of OFET geometry is also considered through specific coefficient.

Proposed model is incorporated in OFET current-voltage characteristics.

Acknowledgements

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