

# Simulated influence of bulk traps on the subthreshold characteristics of an organic field effect transistor

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## Abstract

The subthreshold characteristics of a prepared organic field effect transistor based on regioregular poly(3-dodecylthiophene) (P3DDT) and using poly-4-vinylphenol (P4VP) as the gate insulator have been investigated. The transistor turn-on occurs at a threshold voltage of around  $V_{th} = 0V$ . The (hole) mobility of  $0.002 \dots 0.005 \text{ cm}^2/\text{Vs}$  has been estimated from the linear region of the transfer characteristics. As usually observed for organic transistors, the inverse subthreshold slope is very high, in our case  $S \approx 7V/\text{dec}$ . Furthermore, the subthreshold current depends on the drain voltage although the transistor is a long channel device. One possibility to explain these peculiarities are interface traps, as demonstrated recently by us. In this paper, the influence of bulk traps is shown. It turns out that both the high inverse subthreshold slope and the drain voltage dependency can also be explained by recharging of bulk traps. Therefore, other frequency and temperature dependent dynamic measurements have to be applied to distinguish between the different possible influences.

## 1. Introduction

Organic field effect transistors (OFET) are very attractive for low-cost and low-performance applications, such as organic displays [1] and all-polymer integrated circuits [2]. However, in spite of present success there remain many open problems caused also by the poor material quality due to defects and traps [3]. The influence of bulk traps on the charge transport in an OFET is investigated in [4]. Short channel effects have been included in an analytical model [5] to explain the subthreshold current dependency on the drain voltage. However, a better understanding of the mode of operation is obtained by two-dimensional simulations. Consequently, we have realized these numerical simulations to investigate the subthreshold behavior of the prepared organic transistor.

## 2. Experimental

The preparation of the measured OFET is described in more detail in [6]. The thicknesses of the active layer and the organic insulator are 30nm and 500nm, respectively. The channel length is  $L = 2\mu\text{m}$  and the width  $w = 10\text{mm}$ . In Fig. 1 the measured transfer characteristics are shown on a logarithmic scale. The hole mobility is estimated from the transfer characteristics in the linear region. We obtain  $\mu_p = 5 \times 10^{-3} \text{ cm}^2/\text{Vs}$  at a drain voltage of  $-5V$  and  $-10V$  and  $\mu_p = 2 \times 10^{-3} \text{ cm}^2/\text{Vs}$  at  $V_{DS} = -1V$ . The transistor turns on at a threshold voltage of  $V_{th} = 0V$  estimated from the linear representation of the transfer characteristics. The subthreshold behavior is well described by the inverse subthreshold slope ( $S$ ). At a drain voltage of  $V_{DS} = -1V$  we obtain  $S = 7.7V/\text{dec}$ , which is a very high value even for organic transistors. Furthermore, the subthreshold current depends on the drain voltage, an effect known from

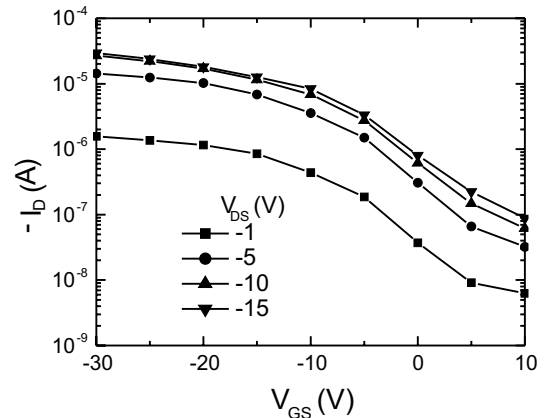


Figure 1. Transfer characteristics of the thin film transistor with  $w/L = 5000$ ,  $d_{P3DDT} = 30\text{nm}$  and  $d_{P4VP} = 500\text{nm}$ .

inorganic transistors but only with short channels. One possible reason for these peculiarities is described in [6]. There the influence of traps at the interface to the insulator has been investigated. Both the high inverse subthreshold slope and the drain voltage dependency can be explained by such interface states. However, besides the interface traps, the inverse subthreshold slope of the transfer characteristics is also influenced by variations of the occupancy of bulk charges, i.e. by incomplete ionized dopands or bulk traps as seen directly from the following equation

$$S = U_T \ln 10 \left( 1 + \frac{C_d + C_{it}}{C_{is}} \right) \quad (1)$$

where  $U_T$  is the temperature voltage,  $C_{is}$  the insulator capacitance,  $C_{it}$  is a capacitance associated with interface traps and  $C_d$  the depletion capacitance, including bulk traps. Therefore, in this paper we consider the influence of these traps which have been only preliminary mentioned in Ref. [6].

### 3. Simulation with bulk traps

The simulated structure is shown in Fig. 2. The

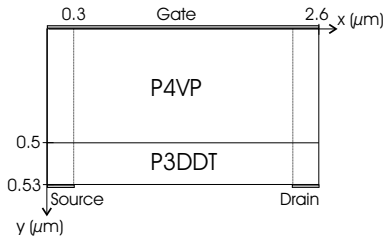


Figure 2. Simulated structure

simulations have been carried out using the program ATLAS [7] which solves the Poisson equation and the continuity equations for the carrier concentrations. For the simulation the same material parameters are used as in [6], i.e. the dielectric constant of the insulator P4VP is  $\epsilon_r = 2.56$ . The parameters of the active layer are the relative dielectric constant  $\epsilon_r = 3.24$ , the monomer density of  $10^{21} \text{cm}^{-3}$ , the energy band gap  $E_g = 2.0 \text{eV}$ , the affinity  $\chi = 3 \text{eV}$  and for the mobilities the values determined before from the transfer characteristics. With regard to the doping concentration, two possible values are used for the simulation, assuming the presence of interface traps, i.e. the threshold voltage can be obtained either by assuming  $N_A = 10^{16} \text{cm}^{-3}$  and no fixed interface states or a value of  $N_A = 3 \times 10^{17} \text{cm}^{-3}$  and a positive fixed charge of  $N_{if} = 9 \cdot 10^{11} \text{cm}^{-2}$ . Consequently, to describe the influence of acceptor-like traps (neutral if empty and negative if occupied by an electron) the lower doping concentration is assumed and for donor-like traps (positive if empty and neutral if occupied) the higher one. At first, the influence of acceptor bulk traps is investigated. The influence of the trap concentration on the transfer characteristic at  $V_{DS} = -5 \text{V}$  is shown in Fig. 3. For this purpose, a

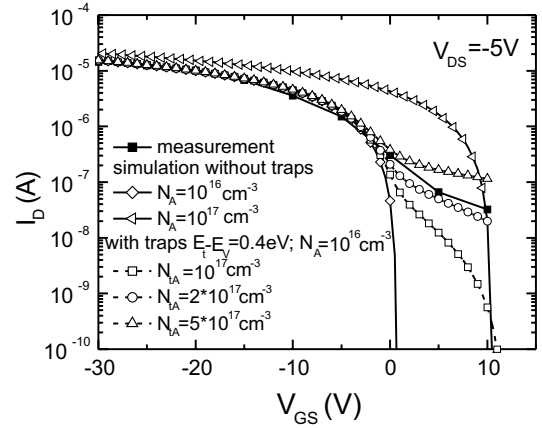


Figure 3. Simulated logarithmic transfer characteristics with acceptor-like and without bulk traps at  $V_{DS} = -5 \text{V}$  compared to the measured curve.

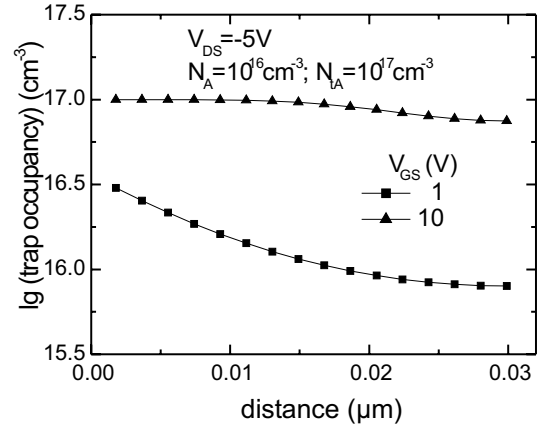
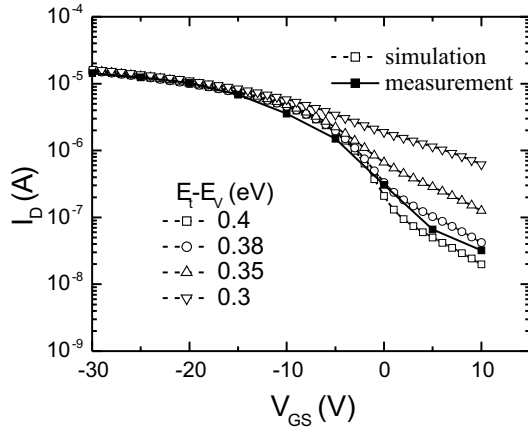


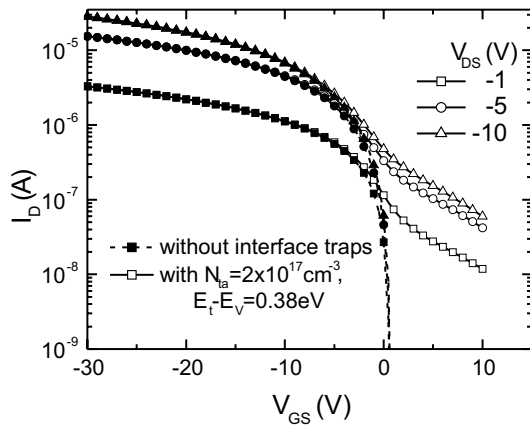
Figure 4. Occupancy of the bulk traps of a density of  $10^{17} \text{cm}^{-3}$  at  $V_{DS} = -5 \text{V}$  and different gate voltages (cross section in the middle of the channel at  $x = 1.3 \mu\text{m}$  perpendicular to the interfaces).

trap level of  $0.4 \text{eV}$  above the valence band is assumed. For comparison, the simulated curves for different doping concentrations without traps and the measurement are also depicted. To explain the impact of the bulk traps on the drain current the trap density of  $N_{tA} = 10^{17} \text{cm}^{-3}$  is considered. Above the threshold voltage there is no difference between the simulations with and without traps. At positive gate voltages up to  $V_{GS} \approx 10 \text{V}$  the drain current and the inverse subthreshold slope increase assuming traps. For higher gate voltages, the current is approximately the same as calculated without traps and a doping concentration of  $10^{17} \text{cm}^{-3}$ . In order to clarify the reason for the drain current behaviour, the trap occupancy is shown in Fig. 4 (cross section in the middle of the channel perpendicular to the interface). At  $V_{GS} = 1 \text{V}$ , the occupancy of the traps from the interface to the insulator up to the middle of the layer is higher than the dop-

ing concentration. The associated negative charge causes an increase of the hole concentration, approximately by a factor of  $10^5$ , and consequently a higher drain current. At  $V_{GS} = 10V$ , nearly all traps are occupied by an electron and almost the same behaviour as for the doping of  $10^{17}cm^{-3}$  is obtained. The drain current in the off-state of the transistor increases with increasing trap density. The simulated currents for  $N_{tA} = 2 \cdot 10^{17}cm^{-3}$  are near the measured ones. Hence, for this trap density the influence of the trap level is shown in Fig. 5a. The occupancy of the more shallow traps is higher causing higher drain currents at positive gate voltages. The simulated curve with a trap energy of 0.38eV above the valence band describes the experimental curve well. For these trap parameters the drain voltage dependency is simulated and compared to

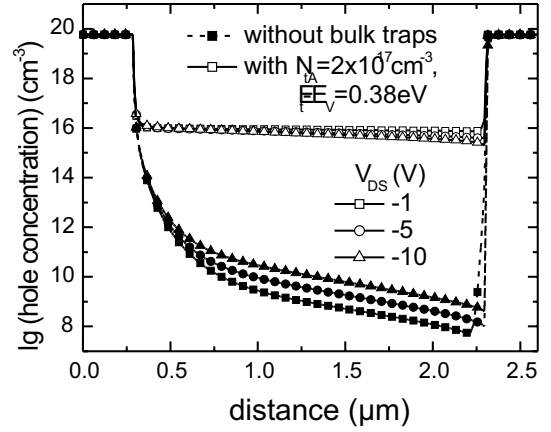


(a)

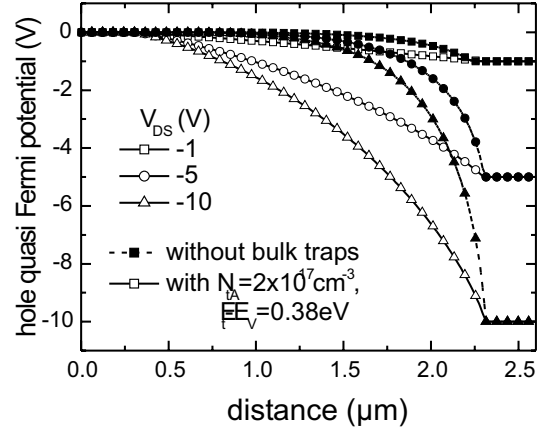


(b)

Figure 5. Simulated logarithmic transfer characteristics with acceptor-like and without bulk traps for different drain voltages.



(a)



(b)

Figure 6. Hole concentration (a) and quasi-Fermi potential (b) along the channel for different drain voltages for  $V_{GS} = 1V$  (cross section at  $y = 0.529\mu m$ )

the result without traps (Fig. 5b). There is no difference between these two cases in the linear and saturation region. However, in the subthreshold region the inclusion of the bulk traps does not only increase the subthreshold slope, but in addition the drain current is higher and depends on the drain voltage. The hole concentrations and hole quasi-Fermi levels in Fig. 6 show the reason for this behavior. The negatively charged bulk traps cause a higher hole concentration in the layer (approximately by a factor of  $10^6$  even at the interface to source and drain Fig. 6a). Therefore, in spite of the reduced gradient of the quasi-Fermi potential (Fig. 6b) the drain current increases at a given drain voltage. Furthermore, the increase of the gradient of the quasi-Fermi potential with increasing drain voltage cause the drain voltage dependency of the cur-

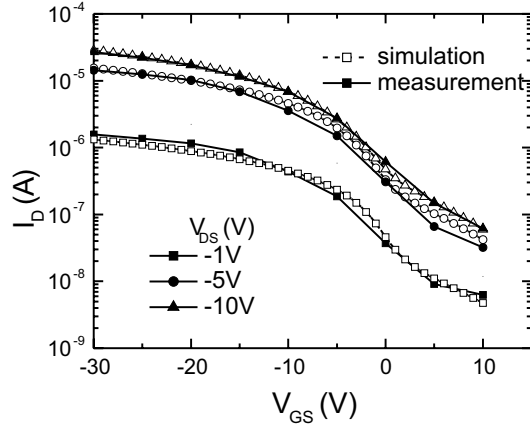


Figure 7. Comparison of measured and simulated transfer characteristics for different drain voltages. The acceptor-like bulk trap density is  $N_{tA} = 2 \times 10^{17} \text{cm}^{-3}$  at an energy of 0.38eV above the valence band.

rent in the subthreshold region. The comparison between the simulated transfer characteristics with acceptor-like bulk traps and the measured curves at different drain voltages (Fig. 7) shows a good agreement of the curves above the threshold voltage and also in the subthreshold regime. Consequently, acceptor-like bulk traps can also be the reason for the peculiarities of the organic transistor.

The influence of donor-like traps has been simulated, too but they are not shown here. For these simulations, a higher doping concentration of  $N_A = 3 \times 10^{17} \text{cm}^{-3}$  is supposed. The best agreement with the measured curves has been obtained assuming a trap density of  $N_{tD} = 3 \cdot 10^{17} \text{cm}^{-3}$  and the same energy level of  $E_t - E_v = 0.38 \text{eV}$  as for acceptor traps.

To be able to discuss the influence of incomplete ionized dopants simulations without traps have been carried out varying the acceptor energy level. It is always difficult to distinguish between bulk traps and incomplete ionized acceptors. If the acceptor level is close to the valence band, all of the acceptors are ionized, there are no recharging processes and hence, no contribution to the depletion capacitance so that the value of  $S$  is equal 200mV/dec. Therefore, to obtain a higher inverse subthreshold slope at positive gate voltages, a higher doping concentration of  $2 \cdot 10^{17} \text{cm}^{-3}$  is supposed. Sequentially, a good agreement between the measured curves and the simulated ones is obtained assuming the same density and the same energy level as supposed for bulk traps.

#### 4. Conclusions

Thin film transistors with regioregular P3DDT as the active semiconductor and P4VP as the gate insulator have been prepared. The threshold voltage of  $V_{th} = 0 \text{V}$  and a mobility of  $0.002 \dots 0.005 \text{cm}^2/\text{Vs}$  have been estimated from the linear region of the transfer characteristics. The inverse subthreshold slope (visible in the log-

arithmic curves) is very high and the current features a drain voltage dependency in the subthreshold regime. The two-dimensional simulations, demonstrated here, show that these peculiarities of the organic transistor can be caused by recharging of incomplete ionized acceptors or bulk traps. In both cases, the recharging process cause the degradation of the subthreshold slope and also the drain voltage dependency of the subthreshold current in a certain gate voltage region. However, as described in [6], also interface traps can cause such effects and it is not easy to separate the influence of the different possibilities. Consequently, to obtain clear without ambiguity results with regard to the material and trap parameters, further experimental methods have to be applied. Frequency and temperature dependent dynamic measurements (for instance described in [8] for SiC transistors) are a matter of future work.

#### 5. References

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