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Charge transport in disordered organic field-effect transistors

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ABSTRACT

The transport properties of poly(2,5-thienylene vinylene) (PTV) field-effect transistors (FET) have been investigated as a function of temperature under controlled atmosphere. In a disordered semiconductor as PTV the charge carrier mobility, dominated by hopping between localized states, is dependent on the charge carrier density. The transfer characteristics of PTV FET have been modeled considering the distribution of charge carriers and mobility over the accumulation channel. Good agreement with the experimental data is obtained.

INTRODUCTION

In less than one decade a great interest in conjugated polymers has developed, as a result of their potential application in microelectronic devices [1,2]. In order to improve the charge carrier mobility and the on-off current ratio, which are the most important parameters for field-effect transistors, the mechanism of charge transport has to be studied. Solution processed thin films made from conjugated polymer have an amorphous or polycrystalline structure and can be characterized as disordered systems. Therefore it can be expected that the transport of carriers within the organic semiconductor is governed by the hopping between localized states [3].

In order to understand the transfer characteristics of disordered organic FET, it is important to realize that the charge carrier density is not uniformly distributed in the accumulation channel, but decreases from the semiconductor/insulator interface into the bulk. In organic FET the mobility is dependent on the charge carrier density, which results from the hopping model. As a consequence the charge carrier mobility does not take a constant value for a certain gate voltage (V_g) like in standard metal-oxide-semiconductor FET, but a distribution of charge carrier mobilities is present in the disordered organic FET. In the present study the electrical characteristics of PTV FET are modeled with a hopping model by taking into account the charge carrier dependence of the mobility in the active channel.

RESULTS AND DISCUSSION

Organic field-effect transistors are primarily operating in accumulation mode. A negative voltage applied to the gate of a p-type FET gives rise to band bending in the semiconductor and determines an accumulation of holes into the semiconductor next to the interface [4]. At low drain voltages (the linear regime) the current in the accumulation channel is proportional with the electric field (V_d/L), the density of induced charge carriers per unit area (C_iV_g) and the carrier mobility m [5]:

$$I_{sd} = WC_iV_g\mu\frac{V_d}{L} \tag{1}$$

The field-effect mobility is directly calculated by differentiating the channel current with respect to the gate voltage at low drain voltage:

$$\mu = \left.\frac{\partial I_{sd}}{\partial V_g}\right|_{V_d \to 0} \frac{L}{WC_iV_d} \tag{2}$$

Note that this equation is only valid when the mobility does not depend on the gate voltage. The transfer characteristic for PTV transistor at room temperature is shown in figure 1, from which it appears that the field-effect current in the active channel increases stronger than linear with gate voltage. It should be noted that also for a gate-voltage dependent mobility $m(V_g)$ the current in the accumulation channel is given by equation 1. However, in this case the derivation of source-to-drain current function of gate bias is given by:

$$\frac{\partial I_{sd}}{\partial V_g} = WC_i\mu\frac{V_d}{L} + WC_iV_g\frac{V_d}{L}\frac{\partial\mu}{\partial V_g} \tag{3}$$

From equation 3 it directly follows that for a gate-voltage dependent mobility, equation 2 is not valid. In fact, in equation 2 the assumption that all the charge carriers in the accumulation layer have the same mobility is made. But, in amorphous organic films, where the charge carriers are strongly localized, the charge transport can be described by a variable range hopping model

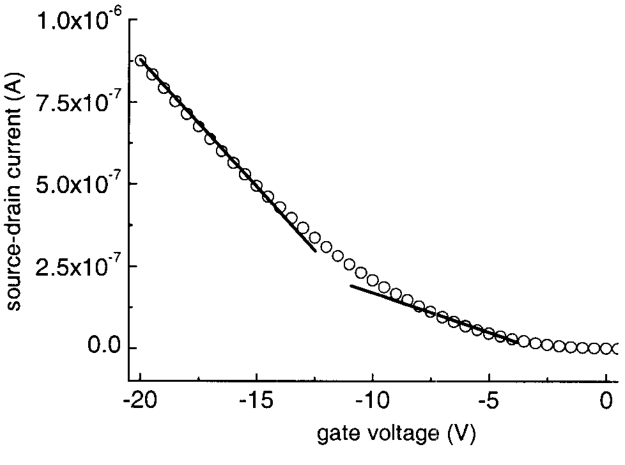

Figure 1. Source-drain current versus gate voltage for PTV field-effect transistor (V_{ds}=-2V) at room temperatures. The solid lines show that the source-drain current has a non-linear behavior.

[3]. The charge carriers move by hopping from a localized state to the next one. By increasing the gate voltage the induced charge carrier density next to the semiconductor/insulator interface is increased [6]. The additional charges will jump easier to neighboring sites. As a result the dependence of the mobility on the gate bias is due to the dependence of mobility on the charge carrier density.

The device characteristics of an amorphous organic transistor have been modeled recently by Vissenberg and Matters [3]. Using an exponential distribution for the density of states and the percolation model of variable range hopping, an expression for the conductivity as a function of density of carriers p and temperature T has been found:

$$\sigma(p,T) = \sigma_0 \left(\frac{p(T_0/T)^4 \sin(\pi T/T_0)}{(2\alpha)^3 B_c} \right)^{T_0/T} \tag{4}$$

Where, s_0 is the prefactor of the conductivity, T_0 is a parameter which indicates the width of the exponential, a^{-1} is the effective overlap parameter between localized states and B_c=2.8 is the critical number at the onset of percolation [3]. From equation 4 it can be observed that the conductivity increases superlinearly with the density of charge carriers ($s \sim p^{T_\circ/T}$). From the conductivity an expression for the local mobility as a function of charge carrier distribution can be derived:

$$\mu_{loc} = \frac{\sigma(p,T)}{ep} = \frac{\sigma_0}{e} \left(\frac{(T_0/T)^4 \sin(\pi T/T_0)}{(2\alpha)^3 B_c} \right)^{T_0/T} p^{T_0/T-1} \tag{5}$$

It can be observed that this equation gives a power law dependence of local mobility with charge carrier density. In order to calculate the field-effect current which flows in the active channel the variation of the charge carriers and the variation of the local mobility from the semiconductor/interface into the bulk is taken into account. Now, the current is calculated over the accumulation layer from the following relation:

$$I_{sd} = \frac{WV_d}{L} \int_0^{x_m} \sigma[p(x),T]dx = \frac{WV_d}{L} \int_0^{x_m} e\mu_{loc}[p(x),T]p(x)dx \tag{6}$$

Where, x_m is the thicknnes of the accumulation layer. In the previously given equation the gradual channel approximation has been used, which means that the potential drop from source electrode to drain electrode is neglected (V_d=-2V). The device measured has a channel of W=2cm in width and L=10µm in length. The transport measurements have been done in the temperature range from 173K to 293K. From temperature dependent measurements on PTV field-effect transistor the fit parameters have been extracted and the following values have been obtained: T_0=382 K, s_0=5.6×10^6 S/m and a^{-1} =1.5×10^{-10}m. Equation 6 is used to model the transfer characteristics of solution processed PTV as a function of temperature and gate voltage. The result of the modeling is shown in figure 2. Good agreement with the experimental data is obtained.

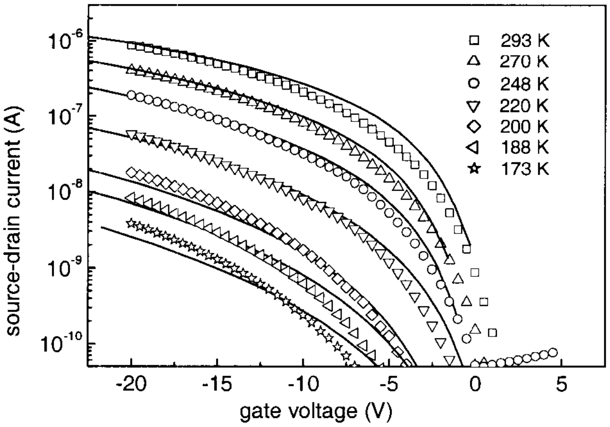

Figure 2. Source-drain current versus gate voltage for PTV field-effect transistor (V_{ds}=-2V) for several temperatures. The solid lines represents the modeling using equation 6.

In order to calculate the local mobility from equation 5, the distribution of charge carriers in the accumulation layer has to be calculated. It is well known that by appling a voltage to the gate electrode a band bending is induced in the semiconductor in the direction *x* perpendicular to the semiconductor/insulator interface [7]. Using an exponential density of states and the Fermi-Dirac occupation function, the density of holes in the active layer is calculated as a function of band bending, which is a function of position.

Considering the charge carrier dependence of the mobility the behavior of the local mobility as a function of position *x* in the accumulation layer is calculated from equation 5 for a gate voltage of V_g=-19.5V, as is shown in figure 3. It can be observed that the local mobility varies with a factor of 6 from 2.1×10^{-3} at the semiconductor/ insulator interface to 4×10^{-4} at a

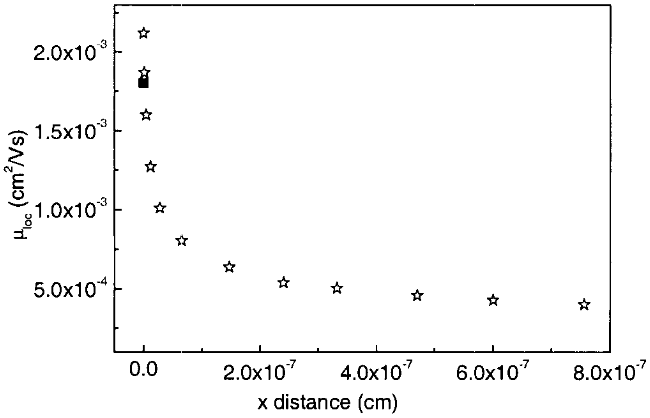

Figure 3. The local charge carrier mobility (stars) and the conventional field-effect mobility (square) in the accumulation channel for V_g=-19.5V.

distance of 7nm from the interface. Thus, due to the charge carrier distribution from the semiconductor/insulator interface into the bulk, the local mobility shows a big variation in the active channel. The difference between the local mobility and the conventional field-effect mobility, which is calculated using equation 2 can be observed in figure 1. Using the standard equation 2 only one value for the field-effect mobility is obtained for a given V_g. The error made using equation 2 instead of equation 5 for V_g=-19.5V at the semiconductor/insulator interface is 18%.

CONCLUSIONS

In this study the transfer characteristics of a disordered organic field-effect transistor have been investigated. Using the variable range hopping concept in an exponential density of states, the charge carrier mobility distribution in the accumulation channel in the direction perpendicular to the insulator has been calculated. The result of modeling of the transfer characteristics are in good agreement with the experimental data.

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