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Switch-on voltage in disordered organic field-effect transistors

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The switch-on voltage for disordered organic field-effect transistors is defined as the flatband voltage, and is used as a characterization parameter. The transfer characteristics of the solution processed organic semiconductors pentacene, poly(2,5-thienylene vinylene) and poly(3-hexyl thiophene) are modeled as a function of temperature and gate voltage with a hopping model in an exponential density of states. The data can be described with reasonable values for the switch-on voltage, which is independent of temperature. This result also demonstrates that the large threshold voltage shifts as a function of temperature reported in the literature constitute a fit parameter without a clear physical basis. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1479210]

The charge transport in organic field-effect transistors has been a subject of research for several years. It has become clear that disorder severely influences the charge transport in these transistors.[1–3] Studies on the effect of molecular order ultimately resulted in the observation of band transport in high quality organic single crystals.[4] The electrical transport in these crystals is well described by monocrystalline inorganic semiconductor physics.[4,5] However, devices envisaged for low-cost integrated circuit technology are typically deposited from solution,[6,7] resulting in amorphous or polycrystalline films. In these solution-processed organic transistors the disorder in the films dominates the charge transport, due to the localization of the charge carriers. The disorder is observed experimentally through the thermally activated field-effect mobility and its gate voltage dependency.[8–12] A further common feature of disordered organic field-effect transistors is the temperature dependence of the threshold voltage, V_{th},[11,12] which is addressed in this letter. It is argued that V_{th}, as used in literature, is a fit parameter with no clear physical basis. Instead, a switch-on voltage, V_{so}, is defined for the transistor at flatband. We model the experimental data obtained on solution-processed pentacene, poly(2,5-thienylene vinylene) (PTV) and poly(3-hexyl thiophene) (P3HT), with a disorder model of variable-range hopping in an exponential density of states.[9] The modeling shows that good agreement with the experiment can be obtained with reasonable values for the switch-on voltage, which is independent of temperature.

The device geometry and the sample fabrication used in the experiments have been described previously.[13] The films of PTV are truly amorphous whereas the pentacene and P3HT films are polycrystalline. We do not observe any hysteresis in the current–voltage characteristics and the curves are stable with time (in vacuum). The field-effect mobilities in the devices have been estimated from the transconductance[8] at $V_g = -19$ V at room temperature and are given in Table I. For the P3HT transistor described here the processing conditions were not optimized to give the high mobilities reported in literature.[1]

The difficulty of defining a threshold voltage in disordered organic transistors was already pointed out by Horowitz *et al.*[14] The threshold voltage in inorganic field-effect transistors is defined as the onset of strong inversion.[5] However, most organic transistors only operate in accumulation and no channel current in the inversion regime is observed, except in high quality single crystal devices.[4] Nevertheless, classical metal–oxide–semiconductor field effect transistor (MOSFET) theory is often used to extract a V_{th} from the transfer characteristics of organic transistors in accumulation. The square root of the saturation current is then plotted against the gate voltage, V_g. This curve is fitted linearly and the intercept on the V_g axis is defined as the V_{th} of the transistor. For disordered transistors this method neglects the experimentally observed dependence of the field-effect mobility on the gate voltage.[8,15] In an attempt to take this into account in the parameter extraction several groups have used an empirical relation to fit the field-effect mobility[12,16]

$$\mu = K(V_g - V_{th})^{\gamma}, \tag{1}$$

where K, γ, and V_{th} are fit parameters. Fitting of current–voltage characteristics of the transistors, using either this empirical relation or the square root technique, has resulted in a temperature dependent V_{th}.[12,17] The temperature dependence is as large as 15 V in the temperature range of 300–50 K.[12]

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TABLE I. Values obtained by using Eq. (6) to model the transfer characteristics of solution processed pentacene, PTV and P3HT. T_0 represents the width of the exponential density of states, σ_0 is the conductivity prefactor, α^{-1} is the effective overlap parameter, V_{so} is the switch-on voltage, and μ_{RT} the field-effect mobility at $V_g = -19$ V and room temperature.

	T_0 (K)	σ_0 (10^6 S/m)	α^{-1} (Å)	V_{so} (V)	μ_{RT} (cm^2/V s)
PTV	382	5.6	1.5	1	2×10^{-3}
Pentacene	385	3.5	3.1	1	2×10^{-2}
P3HT	425	1.6	1.6	2.5	6×10^{-4}

However, for transistors based on the same materials in the crystalline phase, for which the MOSFET theory is valid, the shift of V_{th} with temperature is at most $\simeq 0.5$ V.[2,5] This observation raises the question: why, for a disordered system, the shift of V_{th} with temperature is so much larger than in its crystalline counterpart. To answer this question, we first have to realize that, in both types of analysis mentioned, the extracted V_{th} is a fit parameter. This fit parameter has no direct relation with the original definition of the threshold voltage in the MOSFET theory. Also, depending on the range of V_g over which the data are fitted in disordered transistors, the value of the extracted V_{th} will be different. Therefore, the physical meaning of V_{th} and its temperature dependence in disordered organic transistors are questionable. We will therefore refer to V_{th} here as an "apparent" threshold voltage. Despite these issues, some suggestions have been given in literature to explain the large temperature dependence of the apparent V_{th}, such as a widening of the band gap,[17] and displacement[12] of the Fermi level with decreasing temperature.

Instead of the apparent V_{th} as characterization parameter, we will use the gate voltage at which there is no band bending in the semiconductor, i.e., the flatband condition. We call this the switch-on voltage, V_{so}, of the transistor. Below V_{so} the variation of the channel current with the gate voltage is zero, while the channel current increases with V_g above V_{so}. For an unintentionally doped semiconductor layer, V_{so} is then only determined by fixed charges in the insulator layer or at the semiconductor/insulator interface. In that case V_g becomes $V_g - V_{so}$. Without these fixed charges V_{so} should in principle be zero.[5]

Here we will model the experimental dc transfer characteristics obtained on three different disordered organic field-effect transistors to estimate the temperature dependence of V_{so}. Because we are looking at disordered systems, we use the variable range hopping model proposed by Vissenberg and Matters.[9] The charge transport in this model is governed by hopping, i.e., thermally activated tunneling of carriers between localized states around the Fermi level. The carrier may either hop over a small distance with a high activation energy or over a long distance with a low activation energy. In the disordered semiconducting polymer the density of states (DOS) is described by a Gaussian distribution.[18] For a system with both a negligible doping level compared to the gate-induced charge and at low gate-induced carrier densities the Fermi level is in the tail states of the Gaussian, which is approximated by an exponential DOS[9]

$$g(\epsilon) = \frac{N_t}{k_B T_0} \exp\left(\frac{\epsilon}{k_B T_0}\right), \tag{2}$$

where N_t is the number of states per unit volume, k_B is Boltzmann's constant, and T_0 is a parameter that indicates the width of the exponential distribution. The energy distribution of the charge carriers is given by the Fermi–Dirac distribution. If a fraction, $\delta \in [0,1]$, of the localized states is occupied by charge carriers, such that the density of carriers is δN_t, then the position of the Fermi level is fixed by the condition[9]

$$\delta = \exp\left(\frac{\epsilon_F}{k_B T_0}\right) \frac{\pi T}{T_0 \sin\left(\pi \frac{T}{T_0}\right)}. \tag{3}$$

Using a percolation model of variable range hopping, an expression for the conductivity as a function of the charge carrier occupation δ and the temperature T is derived[9]

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

where σ_0 is the prefactor of the conductivity, B_c is a critical number for the onset of percolation, which is $\simeq 2.8$ for three-dimensional amorphous systems,[19] and α^{-1} is an effective overlap parameter between localized states. To calculate the field-effect current we have to take into account that in a field-effect transistor the charge density is not uniform. Using the gradual channel approximation, we neglect the potential drop from source to drain electrode ($|V_g| \gg |V_{ds}|$). To take into account that the charge-density decreases from the semiconductor-insulator interface to the bulk, we integrate over the accumulation channel

$$I_{ds} = \frac{WV_d}{L} \int_0^t dx\, \sigma[\delta(x), T], \tag{5}$$

where L, W, and t are the length, width, and thickness of the channel, respectively. From Eqs. (4) and (5) we obtain the following expression for the field-effect current:

$$I_{ds} = \frac{WV_{ds}\epsilon_s\epsilon_0\sigma_0}{Le} \left(\frac{T}{2T_0 - T}\right) \sqrt{\frac{2k_bT_0}{\epsilon_s\epsilon_0}}$$
$$\times \left[\frac{\left(\frac{T_0}{T}\right)^4 \sin\left(\pi\frac{T}{T_0}\right)}{(2\alpha)^3 B_c} \right]^{T_0/T}$$
$$\times \left\{ \sqrt{\frac{\epsilon_s\epsilon_0}{2k_bT_0}} \left[\frac{C_i(V_g - V_{so})}{\epsilon_s\epsilon_0} \right] \right\}^{2T_0/T - 1}, \tag{6}$$

where e is the elementary charge, ϵ_0 is the permittivity of vacuum, ϵ_s is the relative dielectric constant of the semiconductor, and C_i is the insulator capacitance per unit area.

Equation (6) is used to model the transfer characteristics of solution processed PTV, pentacene, and P3HT as a function of V_g and T. The four parameters σ_0, α^{-1}, T_0, and V_{so} were used to model all the curves, with a value of $B_c = 2.8$. After this initial fit, each curve was individually modeled with only V_{so} as variable parameter, with the other parameters fixed. From this modeling, no temperature dependence of V_{so} was observed. The results of the modeling are shown in Figs. 1, 2, and 3. The fit parameters are given in Table I. Good agreement is obtained for all three semiconductors.
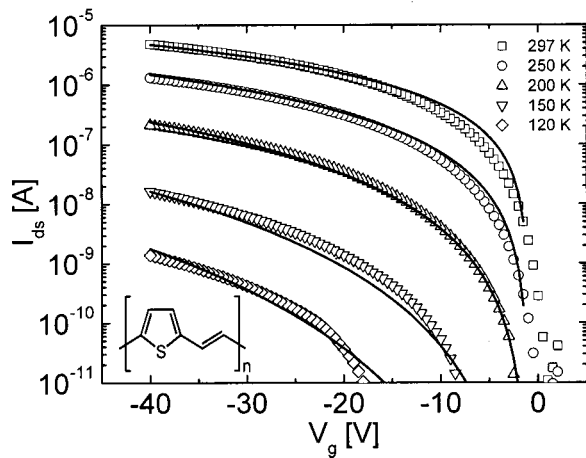
FIG. 1. I_{ds} vs V_g of a PTV thin-film field-effect transistor for several temperatures. The solid lines are modeled using Eq. (6). $W = 2$ cm, $L = 10$ μm, $V_d = -2$ V. The inset shows the structure formula of PTV.

FIG. 3. I_{ds} vs V_g of a P3HT thin-film field-effect transistor for several temperatures. The solid lines are modeled using Eq. (6). $W = 2.5$ mm, $L = 10$ μm, $V_d = -2$ V. The inset shows the structure formula of P3HT.

The single constant V_{so} for all temperatures accounts for any fixed charge in the oxide and/or at the semiconductor-insulator interface. Also, the values obtained for V_{so} are low, which is a realistic situation. Because the measurement resolution in the low current regime is limited to 1–10 pA, the onset of the experimental curves in Figs. 1, 2, and 3, seem to be shifting to more negative gate voltages with decreasing temperature. Logically this effect does not translate in a temperature dependence of V_{so}. Analysis of the data with the square root technique yields an apparent threshold voltage shift with temperature of 15 V for the PTV. Equation (1) gives similar results. We note that, the Fermi level shifting with decreasing temperature[12] has no effect on V_{so}. The Fermi level shift, which results from the Fermi–Dirac distribution of the charge carriers in the exponential density of states, is calculated from Eq. (3) and is found to be $\simeq 0.04$ eV over a temperature range of 200 K. This displacement does not result in a shift of V_{so} with temperature.

In conclusion, it was argued that the threshold voltage extracted from the transfer characteristics of disordered organic transistors, using the MOSFET theory or Eq. (1), is only a fit parameter if 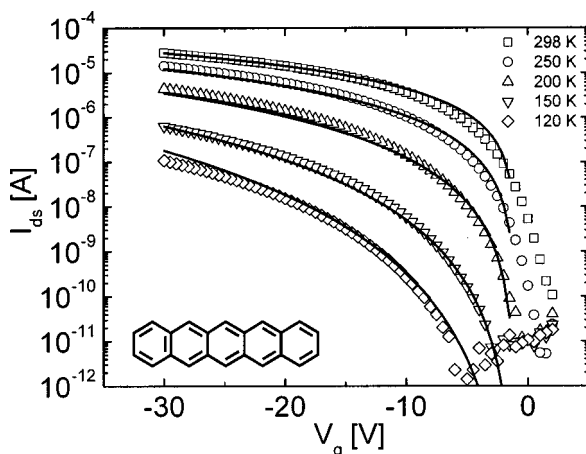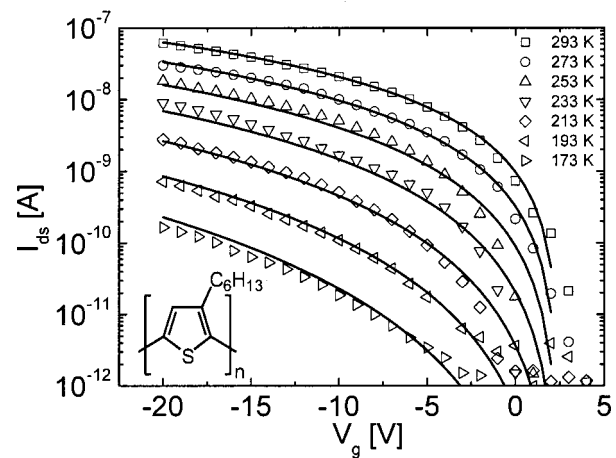the strong inversion regime is not observed in the transfer characteristics. Instead, we have defined a switch-on voltage for unintentionally doped disordered organic field-effect transistors as the gate voltage that has to be applied to reach the flatband condition. Using a disorder model of hopping in an exponential density of states, the experimental data of solution processed PTV, pentacene and P3HT could be described with reasonable values for the switch-on voltage, which is temperature independent. The use of V_{so} as characterization parameter of disordered organic field-effect transistors is not limited to the model described here, but is generally applicable.

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FIG. 2. I_{ds} vs V_g of a pentacene thin-film field-effect transistor for several temperatures. The solid lines are modeled using Eq. (6). $W = 2$ cm, $L = 10$ μm, $V_d = -2$ V. The inset shows the structure formula of pentacene.