An analytical model for organic thin film transistors

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Abstract

An analytical model that describes the DC characteristics of organic thin film transistors (OTFTs) is presented. The model is based on the variable range hopping theory, i.e. thermally activated tunneling of carriers between localized states. As verified by published data, the model provides an accurate and efficient prediction for transfer characteristics and output characteristics of OTFT via simple formulations.

1. Introduction

In recent years, organic thin transistors (OTFTs) have found important application in large-area, low performance and low-cost integrated circuits. Such applications include driving devices for active matrix flat panel displays, organic light identification tags, sensors, etc. The key traits distinguishing field effect transistors with organic active layer from conventional FETs are their potential for low-cost and low-temperature processing, and their compatibility with flexible substrates. As OTFT applications increase, a more accurate and yet simple model of device characteristics is necessary for understanding, improving, and applying these devices. Up to now, many of the numerical or analytical OTFT models use the same expressions as used for for MOS crystalline devices. However, OTFTs present several differences with respect to crystalline MOSFETs because of the low conductivity of organic semiconductors. Furthermore, OTFTs are primarily operated as accumulation field effect transistors as opposed to the usual inversion mode of crystalline MOSFETs. OTFTs are normally conducting at zero gate voltage, and the field-effect mobility usually increases with the gate voltage [1].

In this paper, we derive a basic expression for the sheet conductance based on the variable range hopping (VRH) theory. This theory describes thermally activated tunneling of carriers between localized states (electrons in conduction states) around the Fermi level in the tail of a Gaussian distribution. It has been used to calculate the mobility of OTFTs successfully. After some simplification for the surface potential, simple and efficient analytical expressions for the transfer characteristics and output characteristics are obtained. The model does not require as input parameters the explicit definition of the threshold and saturation voltage, which are rather difficult to evaluate for this kind of device. The obtained results are in good agreement with experimental data.

2. Variable range hopping transport in organic semiconductors

Because most organic films have an amorphous structure, and disorder is dominating the charge transport, variable-range-hopping in positionally and energetically disordered systems of localized states is widely accepted as the conductivity mechanism in organic semiconductors. Different from hopping, where the charge transport is governed by the thermally activated tunneling of carriers between localized states, rather than by the activation of carriers to the extended-state transport level, the concept of variable range hopping means that a carrier may either hop over a small distance with high activation energy or hop over a long distance with a low activation energy. In an organic thin film transistor with a typical structure shown in Fig.1, an applied gate voltage gives rise to an

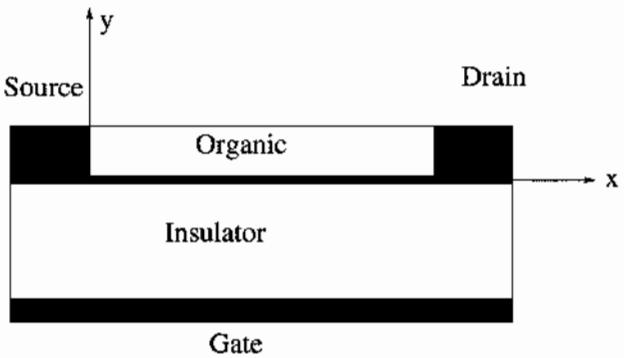

Figure 1. Schematic structure of an organic thin film transistor.

accumulation of charge carriers in the region of the organic semiconductors close to the insulator. As the charges in the accumulation layer fill the low-energy states of organic semiconductors, any additional carrier in the accumulation layer will require less activation energy to hop to a neighboring site. This results in a higher mobility with increasing gate voltage. Connecting percolation theory, Vissenberg studied the influence of temperature and the influence of the filled states on the conductivity based on the variable range hopping theory. The expression of the conductivity as a function of the temperature and car-

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rier concentration is given by [2]

$$\sigma(\delta,T)=\sigma_0\left[\frac{\pi N_t\delta(T_0/T)^3}{(2\alpha)^3B_c\Gamma(1-T/T_0)\Gamma(1+T/T_0)}\right]^{T_0/T}, \tag{1}$$

where σ_0 is a prefactor, α is an effective overlap parameter, which governs the tunneling process between two localized states, and $B_c \cong 2.8$ is the critical number of bonds per site in the percolating network [3], T_0 is the effective temperature, N_t is the number of states per unit volume and δ is the fraction of the localized states occupied by a carrier. The carrier concentration is δN_t, and can be expressed in equilibrium as

$$\rho(V)=N_t\delta(V)=N_t\delta_0\exp\left(\frac{q\Phi}{K_BT_0}\right), \tag{2}$$

where Φ is the electrostatic potential and K_B is the Boltzmann constant, and the δ_0 is the carrier occupation far from the organic-insulator interface.

3. Sheet conductance of the OTFT

From the developed model for amorphous TFT, the drain current I_D can be expressed as [4]

$$I_D=\frac{W}{L}\int_{V_G-V_{FB}-V_D}^{V_G-V_{FB}}G_S(V)dV, \tag{3}$$

where W is the channel width, L is the channel length, V_{FB} is the flat-band voltage, and G_S is the sheet conductance of the channel with $V_D = 0$. The potential V is defined as $V_G - V_{FB} - V_0(y)$, where $V_0(y)$ is the potential at the edge of the space-charge layer where there is no band bending. The basic definition of channel configuration and the variables for the OTFT investigated are illustrated in Fig.2.

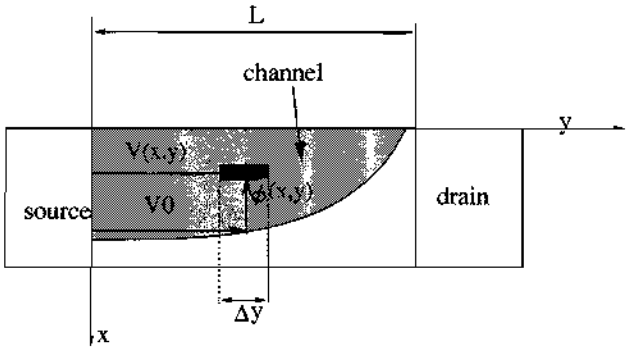

Figure 2. Geometric definition.

The electrostatic potential in the space charge layer at the point (x, y) in the channel is expressed as $V(x,y) = V_0(y) + \Phi(x,y)$, where the $\Phi(x,y)$ is the amount of the band bending in the channel. The conductance for an element of channel length Δy and the width W can be written as

$$G_s=\frac{W}{\Delta y}\int_0^t\sigma dx=\frac{W}{\Delta y}\frac{\sigma(\delta_0,T)}{\sigma_0}\int_0^t\exp\left(\frac{q\Phi}{K_BT}\right)dx \tag{4}$$

where t is the thickness of organic layer. Changing the variable of integration yields

$$G_S=A\int_{\Phi(t(y))}^{\Phi_s(y)}\frac{\exp(q\Phi/k_BT)}{\partial\Phi/\partial x}d\Phi \tag{5}$$

where $\Phi_s(y)$ is the surface band bending and $A = \sigma(\delta_0, T)$. With the identity $\Gamma(1+x)\Gamma(1-x) = \pi x/\sin(\pi x)$ we obtain

$$A=\sigma_0\left[\frac{N_t\delta_0(T_0/T)^4\sin(\pi T/T_0)}{B_c(2\alpha)^3}\right]^{T_0/T}$$

In order to solve (5), we need to get an expression for $\Phi(x)$. By solving Poisson's equation in the gradual channel approximation

$$\frac{\partial^2\Phi(x)}{\partial x}=-\frac{\rho(x)}{\epsilon_0\epsilon_s}, \tag{6}$$

we obtain the electric field.

$$-F_x=\frac{\partial\Phi}{\partial x}\approx\sqrt{\frac{2k_BT_0N_t\delta_0}{\epsilon_0\epsilon_s}}\exp\left[\frac{q\Phi(x)}{2k_bT_0}\right] \tag{7}$$

From (5) and (7), we obtain

$$G_s=A\int_{\Phi(t)}^{\Phi_s}\exp\left[\frac{q\Phi}{k_B}\left(\frac{1}{T}-\frac{1}{2T_0}\right)\right]d\Phi \tag{8}$$

An expression for Φ_s is required. The surface charge density Q_s is related to Φ_s by

$$Q_s=-\epsilon_0\epsilon_sF_s=\sqrt{2k_BT_0N_t\epsilon_0\epsilon_s\delta_0}\exp\left(q\Phi_s/2k_BT_0\right). \tag{9}$$

The surface band bending is related to the applied gate voltage by

$$V_G=V_{FB}+V_i+\Phi_s \tag{10}$$

where V_i is the voltage drop across the insulator,

$$V_i=\frac{Q_s}{C_i} \tag{11}$$

where $C_i = \epsilon_i/d_i$ is the insulator capacitance per unit area. From the equations above, an expression for Φ_s is obtained

$$V_G-V_{FB}-\Phi_s=\gamma\exp(q\Phi_s/(2k_BT_0)) \tag{12}$$

For an accumulation mode OTFT, the surface potential is negative, $\Phi_s \leq 0$, corresponding to $V_G \leq 0$.

$$V_G=V_{FB}+\Phi_s-\frac{\sqrt{2k_BT_0\delta_0N_t\epsilon_0\epsilon_s}}{C_i}\exp\left(-\frac{q\Phi_s}{2k_BT_0}\right) \tag{13}$$

In order to reduce computation time, an explicit yet accurate relation between surface and gate voltage is preferable. In (13), we can get Φ_s using a numerical approach. However, in the accumulation mode, it holds $\exp(-\Phi_s) \gg \Phi_s$, so that an approximate expression of surface potential can be obtained as

$$\Phi_s = -\frac{2k_BT_0}{q} \ln\left[\frac{(V_{FB}-V_G)C_i}{\sqrt{2K_bT_0\delta_0 N_t \epsilon_0 \epsilon_s}}\right] \quad (14)$$

A comparison between numerical calculation and approximate calculation are shown in Fig.(4) and Fig.(5), As can be seen, the agreement is very satisfactory. Parameters are from [5,6].

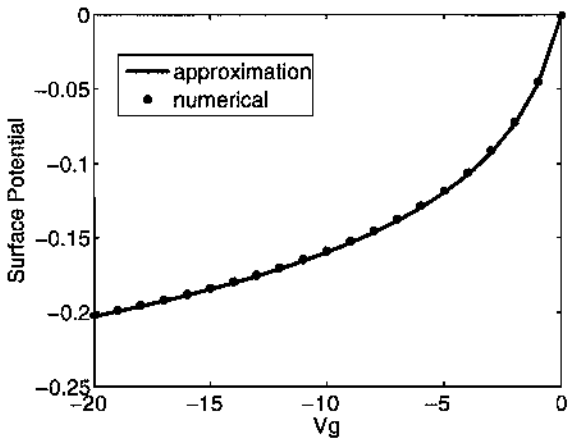

Figure 3. The electrostatic surface potential as a function of gate voltage obtained by the implicit relation (13) and the approximation (14) (solid line).

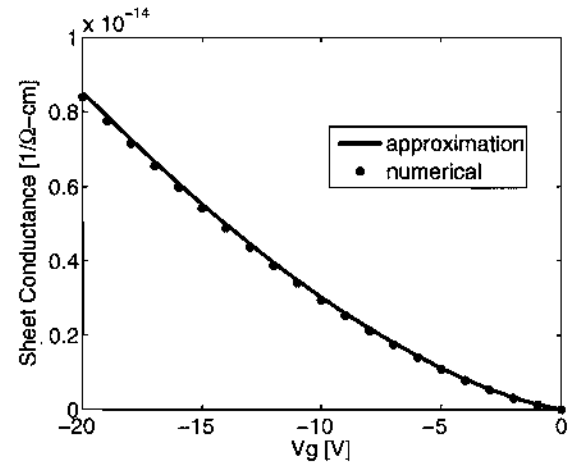

Figure 4. Sheet conductance from numerical calculation (symbols) and the approximation.

With the simplified surface potential and (8), we can get the simplified sheet conductance as

$$G_s = \beta\left[\left(\frac{V_G - V_{FB}}{\gamma}\right)^{2T_0/T-1} - 1\right] \quad (15)$$

For a thick organic semiconductor layer, $\Phi(t) = 0$ and the constants β is

$$\beta = \sigma_0\sqrt{\frac{2\epsilon_0\epsilon_s K_B T_0}{\delta_0 N_t}}\frac{k_BT}{q(T-2T_0)}$$

$$\gamma = \frac{(2\alpha)^3 B_c 2k_B T_0 \epsilon_0 \epsilon_s}{C_i^2 (T_0/T)^3 \sin(\pi T/T_0)}$$

4. Drain current

The drain current can be calculated by substituting the expression of G_s into (3), and we can get

$$I_D = \beta\frac{W}{L}\left[\left(\frac{V_G - V_{FB}}{\gamma}\right)^{2T_0/T} - \left(\frac{V_G - V_{FB} - V_D}{\gamma}\right)^{2T_0/T}\right] \quad (16)$$

in the triode region ($V_{GS} - V_{FB} \geq V_{DS}$) and

$$I_D = \beta\frac{W}{L}\left(\frac{V_{GS} - V_{FB}}{\gamma}\right)^{2T_0/T} \quad (17)$$

in saturation ($V_{GS} - V_{FB} \leq V_{DS}$).

5. Results and Discussion

This model has been confirmed by comparisons between experimental data and simulation results.

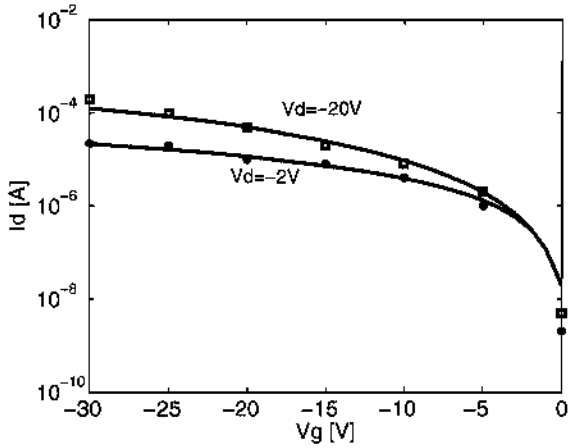

Figure 5. Measured (symbols) and calculated currents of a pentacence OTFT at room temperature.

Input parameters are taken from [5]: $W = 20,000\mu m$, $L = 10\mu m$, $\epsilon_s = 3$, $C_i = 17F/(\mu m)^2$, $\delta_0 = 3.5S/m$, $\alpha^{-1} = 3.1 \times 10^{-10}m$, $T_0 = 385K$.
In Fig.5 and Fig.6, the transfer characteristics of a pentacene OTFT are given for $V_{FB} = 1V$ and different gate voltage and different temperature. Both figures show a good agreement between the analytical model and experimental data. Here we also model the transfer characteristics of a PTF OTFT, where some parameters are different from those for pentacence $T_0 = 382, \delta_0 = 5.6S/m; \alpha^{-1} = 1.5 \times 10^{-10}m$,

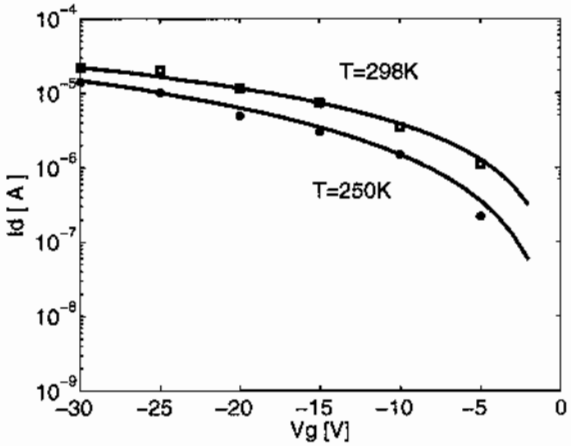

Figure 6. Measured (symbols) and calculated transfer characteristics of a pentacence OTFT at different temperature at $V_D = -2V$.

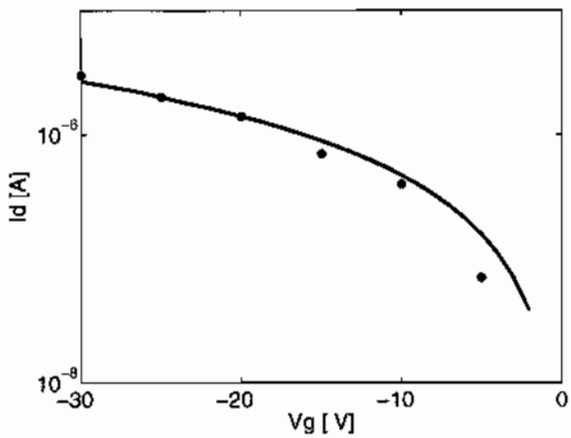

Figure 7. Measured (symbols) and calculated transfer characteristics of a PTV OTFT at room temperature at $V_D = -2V$.

The modeled output charateristics of the pentacene OTFT is shown in Fig.8.

6. Conclusion

An analytical expression has been derived for the sheet conductance of organic thin film transistors on the basis of the variable range hopping transport theory. With a suitable approximation for the surface potential a simple analytical model for the DC characteristcs is derived. The derivation is similar to that presented in [6], however, the present work focuses on the surface potential approximation. A simplified model, obtained in [6] as a reduction of a more complex model, is derived in a direct way. The model shows close agreement with experimental data. The resultant equations can be employed in CAD circuit analysis programs.

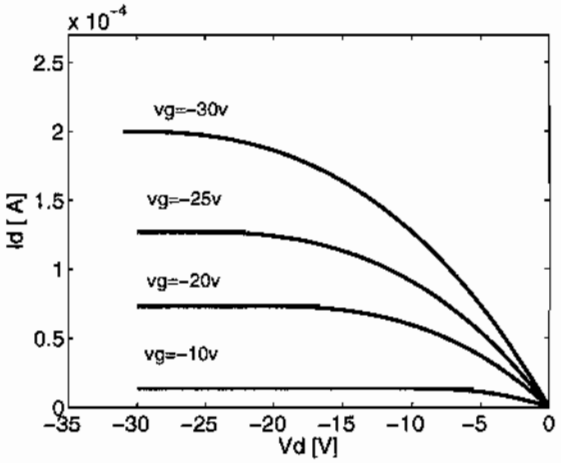

Figure 8. Modeled output characteristics of a pentacene OTFT.

7. Acknowledgment

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