Analytical Current Model for Polymer-based Thin Film Transistors Considering the Field-Dependent Mobility and Nonlinearity in the Linear Region

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Abstract

By using an effective carrier density, we proposed an analytical current model for polymer-based thin film transistors all over the sub- and above threshold regions. We implemented the proposed current model with the reverse Schottky diode model for the nonlinearity and the Poole-Frenkel mobility model for the lateral dependent carrier transport. We verified the proposed model by comparing the measured current characteristics with calculated one and continuity of the output conductance (g_d). We expect that the proposed analytical model can be employed for a fast and efficient circuit simulation.

1. Introduction

Polymer-based thin film transistors (PTFTs) are researched for applications in large area and flexible displays [1] due to low temperature and printing fabrication capability. For a circuit applications, it is important to accurately predict the electrical performance of PTFTs.[2]

In this paper, incorporating the effective carrier density combined with Schottky diode model [3] and Poole-Frenkel mobility [4], an analytical drain current model is reported for all over the gate and drain bias ranges. The proposed model is verified by comparing the measured I-V characteristics with calculated one. For the accuracy of the model, the nonlinearity of the current characteristics under a small drain bias, which commonly showed in PTFTs, are also verified.

2. Schottky contact model

The source-polymer-drain region can be modeled as a series connection of back-to-back connected Schottky diodes with a gate-bias dependent variable channel resistance as shown in Fig. 1. In order to check the Schottky contact, measured 2-terminal C-V characteristics as shown in Fig. 1. It shows to be a symmetric depletion capacitance characteristic over the whole bias range. For an accurate modeling of the Schottky contacts, characterization of the Schottky contact barrier height (ϕ_B) through the I-V characteristic is important as shown in Fig. 1. Through the thermionic field emission current (I_{TFE}), the Schottky barrier height can be extracted as followings:[5]

$$I_{TFE} = \frac{AA^{**}T^2\sqrt{\pi E_{00}}}{kT}\sqrt{\frac{q\phi_B}{\cosh\left(E_{00}/kT\right)}}e^{-q\phi_B/E_0}e^{-qV_R/E'} \tag{1}$$

$$\phi_B = E_0 \ln\left(\frac{AA^{**}T^2\sqrt{\pi E_{00}\phi_B}}{I_{TFE0}kT}\right), E_{00} = \frac{\hbar}{2}\sqrt{\frac{N_A}{m_P^*\varepsilon_P}} \tag{2}$$

$$E_0 = E_{00}\coth\left(\frac{E_{00}}{kT}\right), E' = E_{00}\left[\frac{E_{00}}{kT} - \tanh\left(\frac{E_{00}}{kT}\right)\right] \tag{3}$$

where A, A^{**}, $\hbar$ and m^*_P , ε_P are the contact area, Richardson constant, Planck constant, effective mass of holes, permittivity of the polymer, respectively. With E_{00}=3.51x10^{-4}, E_0=0.026, E'=2.87x10^{-10} are characteristic energies for the thermionic field emission, we finally get the Schottky barrier ϕ_B=0.45 V.

3. Analytical drain current model

In the polymer channel layer, the energy-dependent donor-like DOS (g_D(E)) over the bandgap is modeled as a superposition of exponential deep and tail states as [6]

$$g_D(E) = N_{TD}e^{(E_V-E)/kT_{TD}} + N_{DD}e^{(E_V-E)/kT_{DD}} \tag{4}$$

with E_V as the valence band minimum, N_{TD}(N_{DD}) and kT_{TD} (kT_{DD}) as the effective density of states and the characteristic energy for the donor-like tail(deep) states in the valence band, respectively.

The location along the channel is defined as y and that across the channel as x shown in Fig. 1(a). The trapped holes $p_{loc}(x)$ in g_D(E), trapped holes $p_{deep}(x)$ in the deep states of g_D(E), trapped holes $p_{tail}(x)$ in the tail states of g_D(E), and free holes $p_{free}(x)$ in the valence band are defined as [7]

$$p_{loc}(x,y) = p_{deep}(x,y) + p_{tail}(x,y)$$
$$\begin{cases} p_{deep}(x,y) = N_{DD}kT \times f(T,T_{DD})e^{-q(\phi(x)-V_{CH}(y)-\phi_{F0})/kT_0} \\ p_{tail}(x,y) = N_{TD}kT \times f(T,T_{TD})e^{-q(\phi(x)-V_{CH}(y)-\phi_{F0})/kT_0} \end{cases} \tag{5}$$

$$f(T,T_t) = \begin{cases} \pi/\sin(\pi T/T_t), T_0 = T_t & : kT < kT_t \\ (T/T_t - 1)^{-1}, T_0 = T & : kT > kT_t \end{cases} \tag{6}$$

$$p_{free}(x,y) = N_V e^{-q(\phi(x)-V_{CH}(y)-\phi_{F0})/kT} . \tag{7}$$

We defined T_t as the characteristic temperature of trap states, $\phi(x)$ as the potential across the polymer layer, ϕ_S as the surface potential at polymer/gate insulator interface, $V_{CH}(y)$ as the lateral potential along the channel, $q\phi_{F0}$ as (E_F–E_V), and E_F as the bulk Fermi level under thermal equilibrium. The Poisson's equation across the active region can be written as

$$\frac{\partial^2\phi(x)}{\partial x^2} = -\frac{\rho(x)}{\varepsilon_P} = -\frac{q}{\varepsilon_P}\left(p_{loc}(x) + p_{free}(x)\right) \tag{8}$$

with $\rho(x)$= charge density. Depending on the gate bias (V_{GS}), the charge density $\rho(x)$ in the polymer is approximated by

$$\frac{\rho(x)}{q} \approx \begin{cases} p_{tail} \equiv p_{eff1}(x) & : V_T < V_{GS} < V_{FB} \\ p_{tail} + p_{free}(x) \equiv p_{eff2}(x) & : V_{GS} \approx V_T \\ p_{free}(x) \equiv p_{eff2}(x) & : V_{GS} < V_T \end{cases} \tag{9}$$

and the proposed effective hole density $p_{eff}(x)$ is defined as

$$p_{effi}(x) \equiv P_{effi}e^{-q(\phi(x)-V_{CH}-\phi_{F0})/kT_{effi}},\ i = 1\ or\ 2 \tag{10}$$

where P_{effi} = the effective hole density in the valence band and kT_{effi} =the effective characteristic energy with i=1 or 2 for the sub- or above-V_T region. So, the Poisson's equation can be written as

$$\frac{\partial^2\phi(x)}{\partial x^2} = -\frac{\rho(x)}{\varepsilon_P} = -\frac{q}{\varepsilon_P}p_{effi}(x) . \tag{11}$$

With $\partial[(\partial f(x)/\partial x)^2]/\partial x = 2[\partial f(x)/\partial x]\cdot[\partial^2 f(x)/\partial x^2]$, the electric field ($E_P(x)$) in the polymer is obtained to be

$$E_P(x) = -\frac{\partial\phi(x)}{\partial x} = \sqrt{\frac{2P_{eff}kT_{effi}}{\varepsilon_P}}e^{-q(\phi(x)-V_{CH}-\phi_{F0})/2kT_{effi}} . \tag{12}$$

The free charge $Q_{FREE}(\phi(x))$ and total charge $Q_{TOT}(\phi(x))$ per unit area as a function of $\phi(x)$ can be obtained to be

$$Q_{FREE}(\phi(x)) = q\int_{\phi(x=T_P)}^{\phi(x)} \frac{p_{free}(\phi(x))}{E_P(\phi(x))} d\phi(x) \quad (13)$$

$$Q_{TOT}(\phi(x)) = Q_{FREE}(\phi(x)) + Q_{LOC}(\phi(x)) = \varepsilon_P E_P(\phi(x)) \quad (14)$$

By combining Eqs. (13) and (14), therefore, we get V_{GS}- & V_{DS}-dependent channel mobility $\mu_P(\phi(x))$ as

$$\mu_P(\phi(x)) = \mu_{Band} e^{\beta\sqrt{|V_{DS}|/L}} \times \frac{Q_{FREE}}{Q_{TOT}} \quad (15)$$

$$= \mu_{Band} e^{\beta\sqrt{|V_{DS}|/L}} \times \frac{A^* e^{qB^*(\phi(x)-V_{CH}(y)-\phi_{F0})}}{\sqrt{2\varepsilon_P P_{effi} kT_{effi}}\, e^{-q(\phi(x)-V_{CH}-\phi_{F0})/2kT_{effi}}}$$

$$A^* = \frac{N_V\sqrt{\varepsilon_P}}{B^*\sqrt{2P_{effi}kT_{effi}}},\quad B^* = -\left(\frac{1}{kT} - \frac{1}{2kT_{effi}}\right),\quad \beta = \sqrt{\left(\frac{q}{kT}\right)^2 \frac{q}{\alpha\pi\varepsilon_P\varepsilon_0}}\quad ,\alpha = 10 \quad (16)$$

with μ_{Band}=the valence band mobility, β=Poole-Frenkel factor, α=effective field factor. Therefore, the drain current I_{DS} is described by

$$I_{DS} = W\frac{dV_{CH}}{dy}\mu_{Band} e^{\beta\sqrt{|V_{DS}|/L}} \frac{A^* N_V}{2P_{eff}kT_{eff}C^*} e^{qC^*(\phi_S - V_{CH}(y) - \phi_{F0})} \quad (17)$$

$$C^* = -\left(\frac{2}{kT} - \frac{3}{2kT_{eff}}\right) \quad (18)$$

Gauss' law applied to the boundary between the polymer and gate insulator gives a nonlinear relation between V_{GS} and ϕ_S through (12) as

$$V_{GS} = V_{FB} + \phi_S + \phi_{ox} = V_{FB} + \phi_S + Q_{TOT}/C_{OX}$$

$$= V_{FB} + \phi_S + \frac{\sqrt{2\varepsilon_P P_{eff} kT_{eff}}}{C_{OX}} e^{-q(\phi_S(y) - V_{CH}(y) - \phi_{F0})/2kT_{eff}}. \quad (20)$$

From Eq. (20), we obtain

$$\frac{\partial V_{CH}(y)}{\partial \phi_S(y)} = 1 - \frac{2kT_{eff}}{q(V_{GS} - V_{FB} - \phi_S)} \quad (21)$$

with V_{FB}= the flat band voltage and C_{OX}=the oxide capacitance per unit area. Finally, we get the drain current equation as

$$I_{DS}(N_{effi}, kT_{effi}) = \frac{W}{L}\mu_{Band} e^{\beta\sqrt{|V_{DS}|/L}} \frac{A^* N_V}{2P_{effi}kT_{effi}C^*}\left(\frac{C_{OX}}{\sqrt{2\varepsilon_P P_{effi}kT_{effi}}}\right)^{-2C^*kT_{effi}}$$

$$\times\left[\frac{1}{(-2C^*kT_{effi}+1)}\left\{(V_{GS}-V_{FB}-\phi_{SS})^{-2C^*kT_{effi}+1} - (V_{GS}-V_{FB}-\phi_{SD})^{-2C^*kT_{effi}+1}\right\} - \frac{1}{-qC^*}\left\{(V_{GS}-V_{FB}-\phi_{SS})^{-2C^*kT_{effi}} - (V_{GS}-V_{FB}-\phi_{SD})^{-2C^*kT_{effi}}\right\}\right] \quad (22)$$

And from the Schottky diode current equation [3] is

$$I_{Schottky} = AA^{**}T^2 e^{-q\phi_B/\eta kT}\left(e^{q|V_{DS}|/\eta kT} - 1\right) \quad (23)$$

Finally, the total drain current over the sub- and above-V_T regions for the PTFT modeled as a series connection of the Schottky diodes at S/D contacts with the V_{GS}-dependent channel resistance can be described by

$$\frac{1}{I_{DS}} = \frac{1}{I_{DS\_sub}(P_{eff1}, kT_{eff1})} + \frac{1}{I_{DS\_above}(P_{eff2}, kT_{eff2})} + \frac{1}{I_{Schottky}}. \quad (24)$$

4. Conclusion

We proposed an analytical drain current model for polymer-based thin film transistors by using an effective carrier density over the below- and above-threshold regions. A PTFT is electrically modeled as a series connection of back-to-back Schottky diodes with V_{GS}-dependent channel resistance. In the analytical drain current model, S/D contacts are modeled as Schottky diodes for a strong nonlinearity in the linear region. The Poole-Frenkel mobility model is incorporated for the lateral field-dependent carrier transport. Analytical *I-V* model was verified by comparing the measured *I-V* characteristics with calculated ones over a wide range of the drain bias. Especially, proposed model reproduces the nonlinearity in the linear region. We expect the proposed analytical model to play a role in the process optimization and efficient design for PTFT-based circuits.

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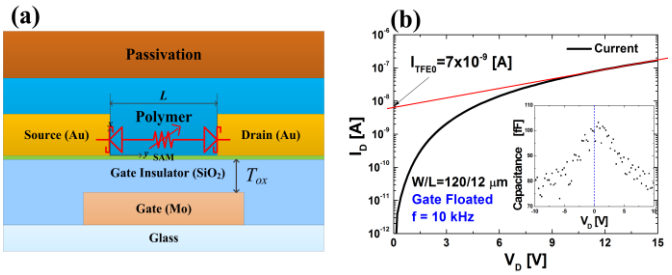

Fig. 1. (a) The cross-sectional view and 2-terminal measure set up of PTFTs. And the (b) *I-V* and *C-V* (inset) characteristics of source-polymer-drain back-to-back Schottky diode.

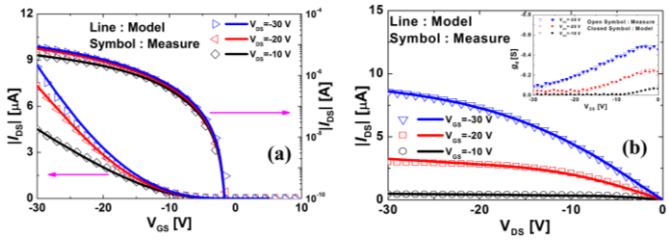

Fig. 2. I_{DS}-V_{GS} characteristics (a) in a linear scale and in a semi-log scale. (b) I_{DS}-V_{DS} characteristics and output conductance are compared with the measured ones for a PTFT with W/L=120 μm /12 μm.

Table I. The structural and extracted parameters for analytical *I-V* model.

Parameter	Value	Parameter	Value
W/L [μm]	120/12	N_V [cm^{-3}]	8.5 x10^{18}
$T_{OX}/T_{Polymer}$ [nm]	300/50	P_{eff1} [cm^{-3}eV^{-1}]	5.26x10^{18}
μ_{Band} [cm^2/V·s]	0.146	kT_{eff1} [eV]	0.031
N_A[cm^{-3}]	3x10^{18}	P_{eff2} [cm^{-3}eV^{-1}]	1.0 x10^{19}
C_{OX} [nF/cm^2]	17.36	kT_{eff2} [eV]	0.0295
m^*_P [kg]	m_0/4	V_{FB} [V]	-1.5
ε_P	3	ϕ_B [V]	0.45