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 ($g_{dy}$). 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 \cite{1} due to low temperature and printing fabrication capability. For a circuit applications, it is important to accurately predict the electrical performance of PTFTs.

In this paper, incorporating the effective carrier density combined with Schottky diode model \cite{3} and Poole-Frenkel mobility \cite{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 ($\phi_b$) through the I-V characteristic is important as shown in Fig. 1. Through the thermionic field emission current (ITFE), the Schottky barrier height can be extracted as followings:\cite{5}

$$I_{TFE} = \frac{AA''T^2}{kT} \sqrt{E_o} \cosh \left( \frac{q\phi_b}{kT} \right) e^{-q\phi_b/kT}$$

(1)

$$\phi_b = E_b \ln \left( \frac{AA''T^2}{kT} \sqrt{E_o} \cosh \left( \frac{q\phi_b}{kT} \right) e^{-q\phi_b/kT} \right)$$

(2)

$$E_o = E_{oa} \cosh \left( \frac{E_{oa} kT}{E_o} \right), \ E' = E_o \left[ \frac{E_{oa} kT}{E_o} - \tan \left( \frac{E_{oa} kT}{E_o} \right) \right]$$

(3)

where $A$, $A''$, $h$, and $m$ are the contact area, Richardson constant, Planck constant, effective mass of holes, permittivity of the polymer, respectively. With $E_{oa}=3.51\times10^{-3}$, $E_o=0.026$, $E'=2.87\times10^{10}$ are characteristic energies for the thermionic field emission, we finally get the Schottky barrier $\phi_b=0.45$ V.

3. Analytical drain current model

In the polymer channel layer, the energy-dependent donor-like DOS ($g_{dy}(E)$) over the bandgap is modeled as a superposition of exponential deep and tail states as \cite{6}

$$g_{dy}(E)=N_{g0}e^{-\left|E-E_{00}\right|/kT_{00}} + N_{g0}e^{-\left|E-E_{00}\right|/kT_{00}}$$

(4)

with $E_r$ as the valence band minimum, $N_{TD}(N_{TD})$ and $kT_D(kT_D)$ 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 $p_{tr}(x,y)$ in $g_{dy}(E)$, trapped holes $p_{dep}(x)$ in the deep states of $g_{dy}(E)$, trapped holes $p_{tail}(x,y)$ in the tail states of $g_{dy}(E)$, and free holes $p_{free}(x)$ in the valence band are defined as \cite{7}

\begin{align*}
\rho_{TR}(x,y) &= \rho_{TR}(x,y) = p_{tr}(x,y) \quad 
\rho_{DEP}(x,y) = N_{TD}kT \times f(T, T_{TD}) e^{-q \left( E_{TD}(x,y) - E_{00} \right) / kT_{TD}} \\
\rho_{PDEP}(x,y) &= N_{g0}kT \times f(T, T_{TD}) e^{-q \left( E_{TD}(x,y) - E_{00} \right) / kT_{TD}}
\end{align*}

(5)

$$f(T, T_{TD}) = \frac{\pi \sin (\pi T/T_{TD})}{(T/T_{TD} - 1)^2}$$

(6)

$$p_{DEP}(x) = N_{TD}kT \times f(T, T_{TD}) e^{-q \left( E_{TD}(x) - E_{00} \right) / kT_{TD}}$$

(7)

We defined $T_r$ as the characteristic temperature of trap states, $\phi_b$ as the potential across the polymer layer, $\phi_b$ as the surface potential at polymer/gate insulator interface, $V_{CT}(y)$ as the lateral potential along the channel, $\phi_{F0}$ 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

$$\frac{\partial^2 \phi_b(x,y)}{\partial x^2} = -\frac{\rho_{tr}(x,y)}{\varepsilon_p}$$

(8)

with $\rho_{tr}(x,y)$ as charge density. Depending on the gate bias ($V_{GD}$), the charge density $\rho_{tr}(x)$ in the polymer is approximated by

$$\rho_{tr}(x) = \begin{cases}
\rho_{PEP}(x) & V_{GD} < V_{GR} \\
0 & V_{GR} \leq V_{GD} \leq V_{TP}
\end{cases}$$

(9)

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

$$\rho_{eff}(x) = \begin{cases}
\rho_{PEP}(x) e^{-q \left( E_{TD}(x) - E_{00} \right) / kT_{TD}} & i=1 \text{or} 2 \\
0 & \text{else}
\end{cases}$$

(10)

where $\rho_{PEP}$ is the effective hole density in the valence band and $kT_{eff}$ is 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

$$\frac{\partial^2 \phi_b(x)}{\partial x^2} = -\frac{\rho_{tr}(x)}{\varepsilon_p}$$

(11)

With $\phi_b = [\phi_b(x,y)]^2 = [2\phi_b(x,y)]^2 \cdot [\phi_b(x,y)]^2$, the electric field ($E_F(x)$) in the polymer is obtained to be

$$E_F(x) = \frac{-\partial \phi_b(x)}{\partial x} = \frac{p_{eff}(x) E_{oa} kT}{\varepsilon_p} e^{-q \left( E_{TD}(x) - E_{00} \right) / kT_{TD}}$$

(12)

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

$$Q_{FREED}(\phi_b) = \frac{P_{eff}(x) E_{oa} kT}{\varepsilon_p} e^{-q \left( E_{TD}(x) - E_{00} \right) / kT_{TD}}$$

(13)

$$Q_{TOT}(\phi_b) = \frac{P_{eff}(x) E_{oa} kT}{\varepsilon_p} e^{-q \left( E_{TD}(x) - E_{00} \right) / kT_{TD}} - \frac{Q_{FREED}(\phi_b)}{\varepsilon_p}$$

(14)
\[ Q_{PREX}(\phi(x)) = q \int_{\phi(x)}^{\phi(x) + \Delta \phi} P_{PREX}(\phi(x)) \, d\phi \] (13)

\[ Q_{EX}(\phi(x)) = Q_{PREX}(\phi(x)) + Q_{EXC}(\phi(x)) = \epsilon_j E_j(\phi(x)) \] (14)

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

\[ \mu(\phi(x)) = \mu_{base} \epsilon_0 \frac{d}{d\phi} \frac{Q_{PREX}(\phi(x))}{Q_{PREX}(\phi(x))} \]

\[ A' = \frac{N_i}{2 q E_0} \left[ 1 - \frac{1}{2 kT_\phi} \right] \quad B' = \left[ \frac{q}{kT_\phi} \right] \quad \beta = \left[ \frac{q}{\alpha \pi \epsilon_i \epsilon_0} \right] \alpha = 10 \] (16)

With \( \mu_{base} \) is the valence band mobility, \( \beta \) = Poole-Frenkel factor, \( \alpha \) is effective field factor. Therefore, the drain current \( I_{DS} \) is described by

\[ I_{DS} = W dV_{TH} \frac{\mu_{base} \epsilon_0}{2 q E_0} A' B' e^{-\left[(h_{\nu_a})/(\nu_a + 1)\right]} \] (17)

\[ C' = \left[ 2 \frac{kT_\phi}{q} - 3 \right] \] (18)

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

\[ V_{GS} = V_{FB} + \phi_k + \frac{q}{C_{OX}} \] (20)

From Eq. (20), we obtain

\[ \frac{dV_{GS}(y)}{d\phi_k(y)} = 1 - \frac{2q}{q(V_{GS} - V_{FB} - \phi_k)} \] (21)

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

\[ I_{DS}(N_{ox}, kT_\phi) = W \mu_{base} \epsilon_0 \frac{A' N_i}{2 q E_0} C \left[ \frac{C_{OX}}{2qE_0C_{OX}} \right]^{\nu_a} \]

\[ \times \left[ \left( \frac{1}{2kT_\phi} \right)^{1/2} \right] \left[ \left( V_{GS} - V_{FB} - \phi_k \right) - \left( V_{GS} - V_{0} - \phi_k \right) \right] \]

And from the Schottky diode current equation [3] is

\[ I_{Schottky} = AA'' e^{2qV_{GS}/kBT} \left( e^{qV_{GS}/kBT} - 1 \right) \] (23)

Finally, the total drain current over the sub- and above-\( V_t \) regions for the PFT model is described as a series connection of the Schottky diodes at S/D contacts with the \( V_{GS} \)-dependent channel resistance can be described by

\[ 1 \quad \text{I}_{S/D} = \frac{1}{I_{DS, sub}(P_{eff} 1, kT_{eff})} + \frac{1}{I_{DS, above}(P_{eff} 2, kT_{eff})} + \frac{1}{I_{Schottky}} \] (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 PFT 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 PFT-based circuits.

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References


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Fig. 1. (a) The cross-sectional view and 2-terminal measure set up of PFTTs. 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_{GS} characteristics and output conductance are compared with the measured ones for a PFT with W/L=120 μm/12 μm.

Table 1. The structural and extracted parameters for analytical I-V model.

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<th>Parameter</th>
<th>Value</th>
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<td>W/L [μm]</td>
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<td>T\text{GOx/Pyrene} [nm]</td>
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