Density-of-States Based Numerical and Analytical Models for Solution-Processed Polymer TFTs

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Abstract

In this work, we propose the subgap density-of-states (DOS) based design platform for solution-processed polymer-based thin-film-transistors (PTFTs). For the model simulation, numerical and analytical I-V models were established from experimentally extracted DOS parameters, and verified by comparing the simulation result with the measured characteristics of solution-processed PTFTs.

Keywords: solution process; organic; polymer; thin-film transistors; density-of-states; analytical model; circuit simulation.

1. Introduction

A great deal of attention has been paid recently to organic electronics, driven by their potential applications throughout from flexible displays [1], large area sensors [2], and radio frequency identification tags [3] to flexible processors [4] and customized programmable logics [5]. In these approaches, polymer-based thin-film-transistors (PTFTs) are the fundamental building blocks with their advantages of low-cost, low-temperature process, and compatibility with the solution process such as spin-coating, ink-jet printing, and gravure printing. However, the circuit simulation method for the solution processed PTFTs has been rarely researched yet while a number of OTFTs with high field-effect mobility higher than 0.1 cm²/V·s have been reported using ink-jet printing [6], [7]. As their potential application becomes more diverse and challenging, the demand for device-circuit co-design, which should be described preferably only with the process/material-controlled and experimentally extracted parameters rather than fitting parameters, becomes indispensable in the solution-processed organic integrated circuits. In this work, we developed the numerical and analytical PTFT models based on the process-controlled parameters including subgap density-of-states (DOS; g(E)).

2. Device fabrication and structure

The polymer-based organic semiconductor was dissolved in tetrahydronaphthalene (THN) at a concentration of 0.2 wt%, and then ink-jet printed via Dimatix printer. The fabricated PTFTs with a coplanar structure had the channel width (W)=120 μm, the gate-to-source/drain (S/D) overlap length (LOV)=10 μm, gate insulator thickness (TOX)=300 nm, and thickness of polymer film (TPolymer)=50 nm (confirmed by FIB-SEM), respectively. Fig. 1(a) shows an array of semitransparent polymer transistors printed on a glass substrate. Fig. 1(b) shows a schematic cross-sectional view of the PTFT with a coplanar structure.

![Fig. 1. (a) A photograph of PTFTs and circuit integrated on a glass wafer. (b) A schematic illustration of the integrated PTFT with the bottom gate and bottom source/drain contact structure (with a coupled-Schottky diode model).](image)

3. Density-of-states Based numerical and analytical models

Fig. 2 shows a schematic illustration of g(E) in polymer thin-film materials. The g(E) is comprised of the donor-like states (gD(E)), shallow acceptor-
like states \( (g_{SA}(E)) \), and interface trap \( (D_d(E)) \). The \( g(E) \) modeled by a superposition of exponential tail and deep states and Gaussian shallow states as follows:

\[
g(E) = g_{tr}(E) + g_{sa}(E) + g_{sh}(E) = \sum_{i=1}^{N_{\text{tr}}} \exp \left( \frac{E - E_i}{\Delta E_i} \right) + \sum_{i=1}^{N_{\text{sa}}} \exp \left( \frac{E - E_i}{\Delta E_i} \right) + \sum_{i=1}^{N_{\text{sh}}} \exp \left( \frac{E - E_i}{\Delta E_i} \right) \]

(1)

Fig. 2. A schematic illustration of \( g(E) \) of the polymer material. It consists of donor-like DOS; \( g_{DA}(E) \) (it is extracted from the MFCV spectroscopy) and the shallow acceptor-like DOS; \( g_{SA}(E) \) (it is extracted from a fitting with measured data by numerical model simulation.). The inset shows a schematic illustration of the interface trap density, \( D_d(E) \).

Fig. 3. Extraction of \( g_{tr}(E) \) using the MFCV spectroscopy
(a) The calculated \( C_{GSS} \) from \( f \)-dependent \( C_{GSS} \) characteristics is shown as an inset. (b) Extracted \( V_{GS} \)-dependent \( R_S \) obtained from the high frequency \( Z_{\text{meas}} \) under a fixed \( V_{GS} \) as shown in the inset. (c) Extracted \( g_{tr}(E) \).

The extraction procedure of \( g_{tr}(E) \) by the Multi-frequency C-V (MFCV) spectroscopy is shown in Fig. 3. This method has been published in the [8]. Fig. 4 shows the calculation flow about numerical and analytical current-voltage \( (I-V) \) models. The models start with \( g_{tr}(E) \) obtained by the MFCV spectroscopy. As shown in Fig. 4 (a) Numerical models are based on physics-based parameters not fitting parameters. The \( g_{tr}(E) \) was experimentally extracted, while \( g_{SA}(E) \) and \( D_d(E) \) were extracted from the numerical iteration. The proposed numerical model is expected to be a useful platform for systematic design of PTFTs via the material/process optimization.

Fig. 4. The calculation flow for the numerical & analytical \( I-V \) models with same parameters \( (g_{tr}(E), \mu_{\text{band}}, N_V) \). (a) Numerical model flow: TFT’s structural parameters are given as \( W, L, T_{\text{Polymer}}, T_{\text{OX}} \). The \( g_{tr}(E) \) experimentally extracted then the other parameters \( (N_V, \mu_{\text{band}}) \) are determined. The \( V_{FB} \) & \( E_{\text{tr}} \) are calculated with the potential obtained from the 1-D field solver. (b) Analytical model flow: The input parameters \( (P_{\text{on}}=N_{1D}, kT_{\text{on}}=kT_{\text{D}}, W, L, T_{\text{OX}}, \text{Schottky barrier}(\theta_i)) \) are fixed by known or extracted value. Through the Gauss’ law, calculate the surface potential and then calculate \( I_{\text{DS}} \).

On the other hand, as shown in Fig. 4 (b) the analytical model is based on the effective carrier density combined with a coupled-Schottky diode model (in Fig. 1 (b)) for the non-linearity and the Poole-Frenkel mobility model for the lateral field-dependent carrier transport. We expect that the proposed analytical model can be employed for a fast and efficient circuit design. We obtain an analytical model for drain current caused by the drift of holes in the channel as

\[
I_{\text{DS}}(N_{1D}, kT_{\text{D}}) = \frac{W}{L} \mu_{\text{band}} e^{V_{GS}^{\text{ref}}} \left[ \frac{C_{GS}}{2P_{\text{on}} kT_{\text{D}}} \chi^{2} \right] \left[ \frac{1}{2} \left( \chi^{2} - \frac{1}{\chi^{2}} \right) \right] \frac{1}{kT_{\text{D}}} \left( V_{GS} - V_{TH}^\alpha - \phi_d^{\alpha} \right) \frac{1}{e^{\frac{\alpha}{kT_{\text{D}}}} - 1} \]

(2)

And from the Schottky diode current equation is

\[
I_{\text{Schottky}} = A A^* T^2 e^{-\varphi_d/kT} \left( e^{\varphi_d/kT} - 1 \right)
\]

(3)

Finally, the total drain current over the sub- and above-\( V_I \) 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

\[
I_{\text{DS}} = I_{\text{DS, sub}}(P_{\text{on}}, kT_{\text{D}}) + I_{\text{DS, above}}(P_{\text{on}}, kT_{\text{D}}) + I_{\text{Schottky}}
\]

(4)
device characteristics because most of all parameters relationship between the process/material and the also made it possible to co-design with the definite controlled parameters including DOS. Our approach for solution-processed PTFTs based on the process-controlled parameters including DOS. Our approach also made it possible to co-design with the definite relationship between the process/material and the device characteristics because most of all parameters

4. Conclusion

We reported analytical and numerical I-V models for solution-processed PTFTs based on the process-controlled parameters including DOS. Our approach also made it possible to co-design with the definite relationship between the process/material and the device characteristics because most of all parameters can be controlled by either the process or the material.

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References