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A compact model of organic thin-film transistors for display device

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ABSTRACT

Organic transistor has been widely studied for next generation flexible semiconductor process. In this paper, we proposed the organic thin-film transistors (OTFT) model for the display device at the moderately high temperature (above 273 K). The model based on hopping theory of Gaussian disordered density-of-states (DOS) considers the dependences relationship of the carrier mobility with temperature and carrier concentrations. Charge transport is controlled by carrier jumps from trap states around the Fermi level to tail trap states at large carrier concentrations. The sub-threshold model is modified using an exponential function to make the model cover all regimes of OTFT operation. A pentacene-based thin film transistor (TFT) model has been designed using Verilog-A language. The model has been verified by device simulations and measurements.

1. Introduction

Organic thin-film transistor (OTFT) is gaining more and more attention in some application areas such as AMOLED displays [1–4], RFID tags [5] and sensor. Therefore, it is fundamental to have specific and accurate analytical spice-like models to simulate and analysis the OTFT display device. Electronic design automation (EDA) tools for organic integrated circuit design will be crucial for increasing the development speed of OTFT technology, speeding its transition from laboratory to application. Some OTFT models have been developed in recent years. Basically, they can be divided into two classes. Some analytical models for the current-voltage characteristics of OTFT are derived [6–8], which cover operation regimes of thin-film transistor linear and saturation. The other models based on the variable range hopping (VRH) theory with exponential DOS [9,10] are widely studied. Nevertheless, like the work of Bässler [11–13], the VRH theory is only applicable at the very low operating temperature (less than 250 K) and fails to correctly describe the relationship of the carrier mobility with temperature and concentration. As a consequence, many commercially available spice models and studied common OTFT models do not accurately contain the physical characteristic of OTFTs specially applied to the thin-film transistor. In this paper, we proposed the bottom-gate bottom-contact (BGBC) pentacene OTFT model for the flexible display panel based on the moderately high temperature. The model incorporates a temperature and concentration dependent mobility featuring a $\ln(\mu) \propto T^{-1}$ law. In the display device, the operating temperature is moderately higher (more than 273 K) and the carrier concentration of the OTFT based on pentacene is larger ($n/N \geq 10^{-2}$) [13]. In the linear and saturation regime, the deep states are occupied so that charge transport is controlled by carrier jumps from trap states around the Fermi level to the tail states of a Gaussian disordered DOS [11] whereas in the sub-threshold regime, the model is modified by the exponential function where the current is controlled by deep states of exponential DOS. Finally, the model has been verified by device simulations and measurements from the literature [4].

2. OTFT model

To avoid metal-deposition damage on an OTFT, the BGBC configuration OTFT is adopted in the flexible display panel, as shown in Fig. 1(a). The semiconductor layer is organic small-molecule pentacene. y represents the direction parallel to the current flow and x represents the perpendicular one. The energy band structure in the pentacene-insulator interface is shown in Fig. 1(b). In the disordered organic semiconductor, the charge transport is described by the hopping mechanism between discrete trap states in the energy gap. In the high carrier concentration, the deep states near the centre of the energy gap can be filled by carriers. Charge transport is controlled by carrier jumps from trap states around the Fermi level to the tail states. The distribution of the tail states is represented by a Gaussian distribution [11].

$$g(E) = \frac{N}{\sqrt{2\pi\sigma^2}} \exp(-E^2/2\sigma^2) \tag{1}$$

where N is the total trap states, E is an arbitrary energy in the energy gap and σ is the width of the Gaussian disorder distribution. In

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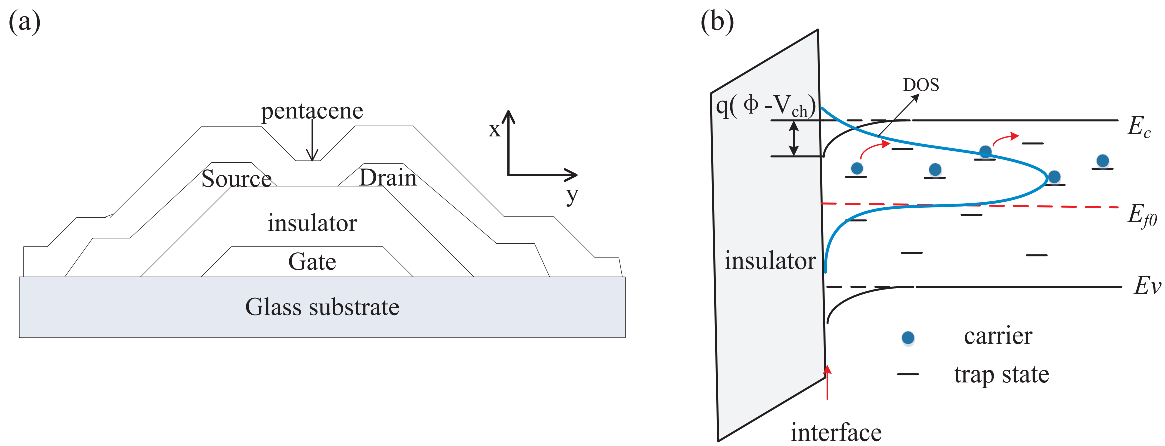

Fig. 1. (a) OTFT cross section of the flexible AMOLED display, and (b) a band diagram in the pentacene-insulator interface.

Table 1
Physical and geometric parameters of the OTFT model.

Model Parameter	Notation	value
Channel width/length	W/L [μm]	80/5
Gate capacitance	Ci [nF/cm^2]	70
Zero-Field mobility	μ_0 [$cm^2/(Vs)$]	2.5
Trap DOS	N [cm^{-3}]	10^{22}
Energy disorder parameter	σ [eV]	$3k_BT$
Flat voltage	V_{fb}[V]	4.5
Temperature	T [k]	300
Fitting parameter	η	−12
Fitting parameter	μ_{sub}[$cm^2/(Vs)$]	0.065

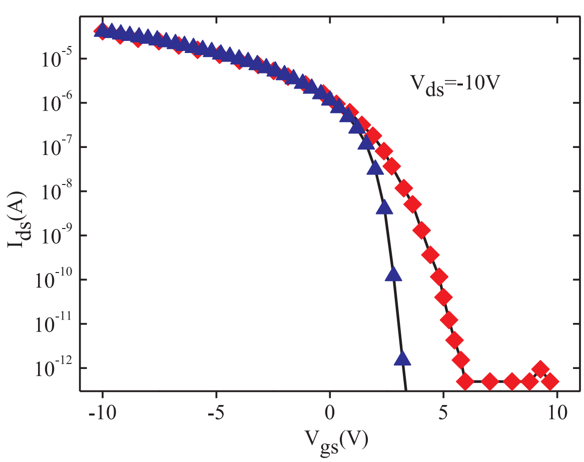

Fig. 2. Transfer characteristics of modeling (Blue triangles) without sub-threshold regime and measured (Red rhombus). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

pentacene, the typical value of σ is $3k_BT$, where k_B is the Boltzmann constant and T is the temperature. Consequently, the carrier concentration is expressed by

$$n = \int_{-\infty}^{+\infty} g(E)f(E)dE, \quad f(E) = \frac{1}{1 + \exp[(E - E_F)/k_BT]} \tag{2}$$

where $f(E)$ is the occupation probability of the trap states. The expression of $f(E)$ is followed by the Fermi-Dirac distribution, and E_F is the Fermi level. It is worth notice that the Fermi level is not a constant but is related to the gate-induced potential φ and the channel potential V_{ch}. As shown in Fig. 1(b), as the gate voltage increases, the charges are accumulated in the pentacene-insulator interface so that the energy band bends and the Fermi level E_F is gradually lifting to the band edge. The Fermi level E_F, as shown in Fig. 1(b) in dot line, is located

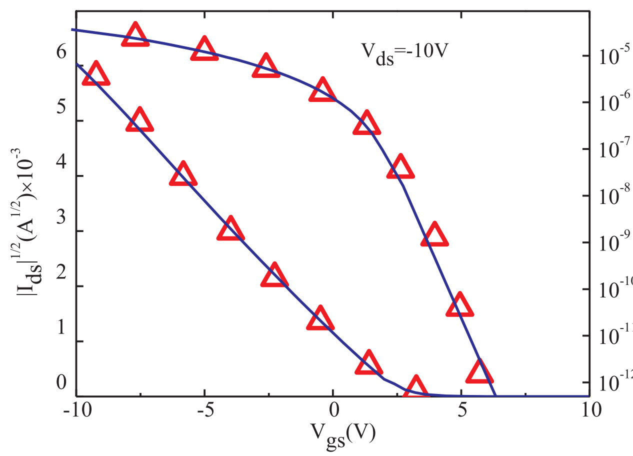

Fig. 3. Transfer characteristics of modeling (Solid line) and measured (Symbols) with sub-threshold regime.

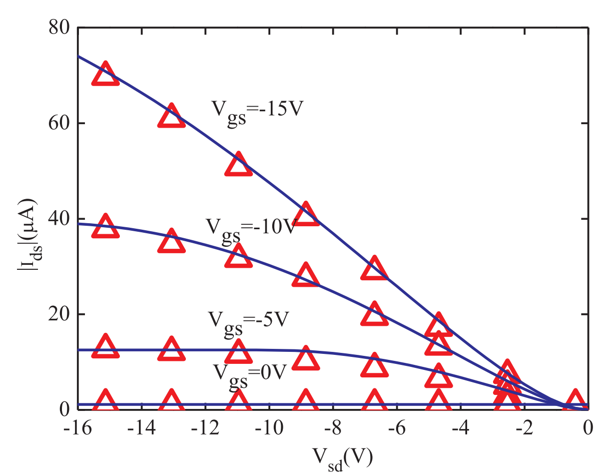

Fig. 4. Transistor output characteristics of modeling (Solid line) and measured (Symbols).

within the occupied DOS, so $E - E_F \geq 2k_BT$ is not satisfied. Then, the occupation probability of the trap state cannot be approximated by the Boltzmann distribution. Therefore, the carrier concentration may be described as [14].

$$n = n_0 \exp\left[\frac{q(\varphi - V_{ch})}{k_BT}\right] \tag{3}$$

where the carrier concentration n depends on the distance x through the gate-induced potential $\varphi(x)$ and the channel voltage V_{ch}, n_0 is the