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Static and dynamic modeling of organic thin-film transistors for circuit design

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ABSTRACT

A new static and dynamic model for organic thin-film transistors (OTFTs) is proposed. The model incorporates a gate-voltage dependent mobility, drain/source contact series resistance, threshold voltage variation with bias and channel length, and drain induced barrier lowering effect. The model also takes into account all the operating regions and includes static and dynamic characteristics of OTFTs. It is developed using a physical basis where the model's parameters can easily be extracted from the experiment data. The model is suitable for computer aided design applications and has been verified by device simulations and measurements from both p-type and n-type OTFTs.

1. Introduction

Advances in organic semiconductor (OS) technologies have been occurring at an accelerating pace. This technology is particularly attractive due to its low-cost, low temperature process, implementation on flexible and light substrates, novel applications, and the potential to move to more environmentally friendly materials and process. In addition, organic circuits can be manufactured in different shapes, e.g. printed onto curved substrates, knitted into cloth, or even used as fibers directly in fabrics. They can be used in large-area electronic applications such as smart flexible displays, solar cells, flexible microelectronics and electronic skin for robots [1–3]. Organic semiconductors are inherently sensitive to specific molecules, thus organic transistors are ideally suited for biological and chemical sensors. The efficient design of organic integrated circuits requires preliminary optimization and modeling, and the availability of accurate SPICE-like analytical models is particularly attractive.

OTFTs pass current by majority carriers, as opposed to the inversion mode of operation of typical MOSFETs. Many OTFTs models have been proposed in the literature [4–12] to reflect specific charge transport characteristics of particular OTFTs. An efficient and accurate compact device model can provide the bridge between existing OTFT technologies and more traditional circuit design. 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. However, it is difficult to find a widely accepted SPICE-like model which includes static (DC) and dynamic (AC) model based on second order effects of OTFTs [13–16]. In this paper, we propose an advanced compact DC/AC model for OTFTs based on second order effects. The present model has three major improvements: (i) This DC/AC model is based on second effects of OTFTs, such as channel length modulation, contact resistance. (ii) Drain induced barrier lowering (DIBL) effect is considered in this model. (iii)The extended range of application including p-type and n-type. The model covers all the operating regions of OTFTs with a reasonable number of parameters. P type OTFT with organic material Pentacene and n type OTFT with organic material PTCDI-C_{13} were manufactured and analyzed to investigate the validity of the model. The comparative results could be accurately fit between the measured *I–V* characteristics and simulation output with methodically extracted model parameters from the linear region to saturation region.

2. Static model

In a traditional inorganic device, the active semiconductor layer is generally comprised of lightly doped Si, or combination of group III–V elements, such as GaAs. In these materials, the applied gate

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voltage causes an accumulation of minority charge carriers at the dielectric interface, such as electrons in a p-type material termed an 'inversion layer'. Carriers injected from the source and drain electrodes may pass in this shallow channel where the current flow is resulted. In an organic OTFT, the active layer is composed of a thin film of highly conjugated small molecules or polymers, e.g. p-channel pentacene and n-channel PTCDI-C_{13}.Compared to inorganic materials, organics pass current by majority carriers and an inversion regime does not exist. This fundamental difference is related to the nature of charge transport in each of these semiconductors. In well-ordered inorganic material, the delocalization of electrons leads to a band-type mode of transport, with charge carriers moving through a continuum of energy levels. In less-ordered organic materials, the proposed mechanism is hoping between discrete, localized states of individual molecules.

OTFTs are three-terminal electrical devices that allow for the control of the electrical current flowing between two electrodes (source and drain) through the modulation of voltage (or current) at a third electrode (the gate). In the basic OTFT design, there are two types of device configuration: top contact and bottom contact. The former involves building source and drain electrodes onto a performed semiconductor layer, whereas the latter is constructed by depositing the organic over the contacts layer. The structures are illustrated in Fig. 1. The electrodes in the thin-film transistor are composed of a metal. Typically, the electrodes are composed of gold which have to do with the energy barrier, or the contact potential of the metal–semiconductor interface.

A suitable OTFT model must be accurate enough in device simulations but also should present a high level of convergence in integrated circuit simulations. At the same time, the model needs to be flexible enough to take into account differences in OTFTs due to materials and procedures used in fabrication. In order to avoid the divergence, the model should be developed using explicit equations. It has to be analytical, simple and easily derivable. The model performance must be evaluated by comparing the simulation results to device measurements.

In the following discussion, the transistors are assumed to be n-type. For the case of p-type, care must be taken to change the polarities of the voltage applied.

Charge drift is the accepted model in the presence of tail-distributed traps (TDTs). From TFT charge drift model, the current is given by [17]:

$$I_D = W\mu_x Q_x |E_x| \tag{1}$$

where W is the width of the OTFT conduction channel. At given position x in the channel ($0 \le x \le L$), μ_x is mobility and Q_x is the charge density. E_x is the electric field strength.

Parameter Q_x is given by (for $V_{GS} > V_T$):

$$Q_x = C_{diel}(V_{GS} - V_T - V_x) \tag{2}$$

Parameter C_{diel} is the gate dielectric capacitance per unit area, V_{GS} is the voltage between the drain and source, V_T is the threshold voltage and V_x is the voltage at position x.

In order to obtain a better fit to the measured data, a gate voltage dependent mobility is developed [19]. In OTFTs operating above threshold, most of the charge induced by the gate-source voltage occupies localized traps and only a fraction of carriers play a role in current conduction. This effect can be accounted for by the empirical gate-voltage dependent field-effect mobility.

$$\mu_x = \mu_0\left(\frac{V_{GS} - V_T - V_x}{V_{aa}}\right)^{\gamma} \tag{3}$$

where μ_0 is the low-field mobility, γ is the mobility enhancement factor, and V_{aa} is a fitting parameter [18]. These parameters can be extracted from the $I_{DS}(V_{GS})$ characteristics.

Parameter E_x can be written as:

$$|E_x| = \partial V_x/\partial x \tag{4}$$

Integrating Eq. (1) along the channel gives:

$$\int_0^L I_D dx = \int_0^{V_{DS}} W\mu_0 C_{diel}\left(\frac{V_{GS} - V_T - V_x}{V_{aa}}\right)^{\gamma}(V_{GS} - V_T - V_x)dV_x$$

Therefore:

$$I_D = \frac{\mu_0 C_{diel}}{V_{aa}{}^{\gamma}}\frac{W}{L}\frac{(V_{GS} - V_T)^{(\gamma+2)} - (V_{GS} - V_T - V_{DS})^{(\gamma+2)}}{\gamma + 2} \tag{5}$$

2.1. Channel length modulation

Eq. (5) can be modified to allow for channel length modulation:

$$I_D = \frac{\mu_0 C_{diel}}{V_{aa}{}^{\gamma}}\frac{W}{L - \Delta L}\frac{(V_{GS} - V_T)^{(\gamma+2)} - (V_{GS} - V_T - V_{DS})^{(\gamma+2)}}{\gamma + 2} \tag{6}$$

Introducing the channel length modulation coefficient λ,

$$\frac{\Delta L}{L} = \lambda V_{DS}$$

$$L - \Delta L = L\left(1 - \frac{\Delta L}{L}\right) = L\left(1 - \lambda V_{DS}\right) \overset{\lambda V_{DS} < < 1}{\approx} \frac{L}{(1 + \lambda V_{DS})} \tag{7}$$

Therefore, Eq. (6) can be written as:

$$I_D = \frac{\mu_0 C_{diel}}{V_{aa}{}^{\gamma}}\frac{W}{L}*(1 + \lambda V_{DS})* \frac{(V_{GS} - V_T)^{(\gamma+2)} - (V_{GS} - V_T - V_{DS})^{(\gamma+2)}}{\gamma + 2} \tag{8}$$

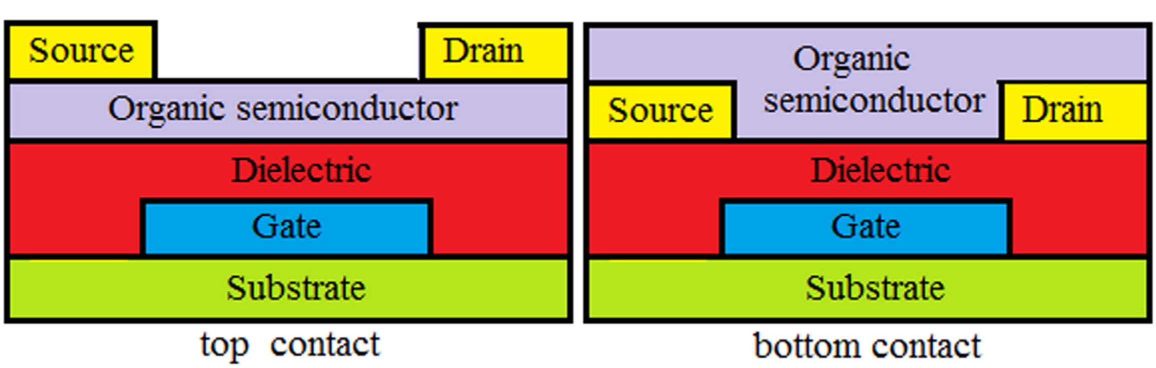

Fig. 1. Simplified diagram of organic thin-film transistor (OTFT).