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Mobility model for compact device modeling of OTFTs made with different materials

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Abstract

In this paper we present a new approach to model mobility in organic thin film transistors, OTFTs, which is used to analyze the behavior of mobility in devices made of poly(methyl methacrylate), PMMA, on poly(3-hexylthiophene), P3HT, recently reported by us. It is also used to discuss differences observed between OTFTs made with other polymers and oligomers. The method allows the calculation of the characteristic temperature and energy distribution of localized states (DOS) in the active layer, considering an exponential distribution. It is also shown that using the extracted DOS parameters as input DOS parameters in ATLAS simulator, it is possible to reproduce very well the device characteristics.

Keywords: Mobility modeling; Extraction of DOS parameters; OTFT modeling

1. Introduction

For the last years, much effort has been dedicated to the development of electronic devices based on both main types of organic materials: oligomers and polymers. These two kinds of organic materials present important differences related to both their properties and methods of preparation. While oligomers are usually obtained by vacuum deposition techniques, polymers are most frequently deposited by spin coating or inkjet printing. Concerning their properties, conductivity and non-intentionally doping is usually lower for oligomers than for polymers; polymers also present a more disordered structure than oligomers. For these reasons, the values of mobility obtained for oligomers can be much higher than those obtained for polymers, while its dependence with the electric field perpendicular to the channel may vary significantly for devices fabricated with different materials. Among oligomers, pentacene has shown highest values of mobility, above 2 $cm^2/V\,s$ [1], while among polymers, P3HT is the one that has presented highest mobility values, above $1 \times 10^{-3}\ cm^2/V\,s$ [2].

Another characteristic of organic materials that can vary significantly from one material to another is the energy distributions of localized states (DOS), which, in addition, can be further modified with annealing processes.

The behavior of I–V characteristics of organic thin film transistors, OTFTs, has been frequently represented using the same expressions as for MOSFETs [3], to which specific effects present in OTFTs as ohmic or non-ohmic resistance at drain and source contacts are added [4,5]. The presence of leakage current through the dielectric layer [6], or across the channel are other features that have also been considered. In [7] we showed that some pentacene OTFTs can be very accurately modeled using the same expression for mobility as for amorphous silicon TFTs. The transistor

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model also included series resistance and non-ohmic contacts. Among the advantages of this method are the simple and precise extraction procedures that can be used to determine all model parameters from the electrical characteristics of the devices. At the same time, model parameters are related to physical properties of the device.

In general, mobility in OTFTs increases with gate voltage, although the law of growth may vary from one material to another. Some authors have reported also a dependence of mobility with V_{DS}, which has been related to a Frenkel–Poole type effect associated to traps in the material [8], as well as to the lowering of the emission barrier in traps located at the boundaries between crystals in polycrystalline materials [9]. A problem not yet solved is the analysis of the subthreshold region for these devices, since the presence of non-ohmic contacts, as well as leakage between drain and source or across the gate can hide the real behavior of the device in this region.

Material properties of polymers as molecular weight, regioregularity and in general its microstructure [10,11], diluents in the case of spin casting deposition techniques [12], as well as involuntary or controlled doping [13,14] can significantly modify not only the value of mobility at low fields, but its variation with temperature and voltage. In addition, processing conditions as thermal annealing will affect the properties of the materials and therefore mobility [12].

For the above reasons, the electrical behavior of organic devices may vary significantly for different materials and structures, which is something that must be taken into account when models are implemented.

From the theoretical point of view several expressions to model mobility as function of different parameters have been obtained. For example, in [14], the dependence of mobility with regioregularity in P3HT was reproduced, calculating mobility as function of charge carrier concentration, considering hopping as main transport mechanism and a double Gaussian DOS. Adjustment with experimental data was achieved by just fitting DOS parameters until agreement was met. In [15], the same approach was used to model the dependence of mobility with doping concentration.

Since, the final goal of these studies is to model the behavior of the transistor, expressions representing the behavior of mobility must be previously obtained to be included in the transistor models.

In this paper we present a new approach to model mobility in OTFTs that allows the extraction of DOS parameters of the organic semiconductor material used in the device.

We use an analytical expression for the mobility, which can be associated to the representation of the mobility as a power law of the gate overdrive voltage $V_{GT} = (V_{GS} - V_T)$. The expression is incorporated to the OTFT model previously presented by us in [7], after which the modeling and extraction procedures already established are complemented to include specific characteristics of polymers. The method is first applied to model the I–V characteristics of top gate devices fabricated with poly(methyl methacrylate), PMMA, as dielectric and poly(3-hexylthiophene), P3HT, as semiconductor layers, [16], as well as to show some specific characteristics of these devices. We also apply it to other OTFTs and discuss the differences observed in the behavior of mobility between devices. Finally, extracted DOS parameters are given as input DOS parameters to ATLAS simulator to compare the agreement between measured and simulated output characteristics.

2. Modeling of mobility

Field effect mobility as function of gate voltage in inorganic amorphous TFTs has been well modeled through the expression:

$$\mu_{FET} = \mu_0 \cdot \frac{(V_{GS} - V_T)^{\gamma}}{V_{aa}^{\gamma}}. \tag{1}$$

This expression can be rewritten as:

$$\mu_{FET} = \frac{1}{(V'_{aa})^{\gamma}} \cdot (V_{GS} - V_T)^{\gamma} \tag{2}$$

where $\frac{1}{(V'_{aa})^{\gamma}}$ is to be extracted.

In [17] we presented a new method to model and extract model parameters to simulate amorphous silicon TFTs, where parameters γ and V_{aa} are independently extracted from measured TFT electrical characteristics. This method is based on an integral function and was called unified model and extraction method (UMEM).

Among theoretical studies of field effect mobility in OTFTs, an interesting approach is found in [18], where using a percolation approach, an expression for mobility is derived and applied to reproduce experimental behavior of OTFTs, one fabricated with pentacene and another with polymer PTV. The expression obtained for the ideal case where flat band voltage V_{FB} is zero was:

$$\mu_{FET} = \frac{\sigma_0}{q} \cdot \left(\frac{\pi \left(\frac{T_0}{T}\right)^3}{(2\alpha_0)^3 B_c \cdot \Gamma\left(1 - \frac{T}{T_0}\right) \cdot \Gamma\left(1 + \frac{T}{T_0}\right)} \right)^{\frac{T_0}{T}} \cdot \frac{(C_i)^{\left(2\frac{T_0}{T} - 2\right)}}{(2k_b \cdot T_0 \cdot \varepsilon_s)^{\left(\frac{T_0}{T} - 1\right)}} \cdot V_{GS}^{\left(2\frac{T_0}{T} - 2\right)}, \tag{3}$$

where C_i is the dielectric capacitance per unit area, α_0 is an effective overlap parameter describing hopping, ε_s is the dielectric constant of the semiconductor layer, σ_0 is an unknown prefactor and B_c is a critical number estimated as 2.8. T_0 is the characteristic temperature of the localized states and k_b is the Boltzmann's constant. For OTFTs working in accumulation, V_{FB} is the voltage required to start accumulation and can be treated as the threshold voltage V_T.