Organic Electronics 15 (2014) 35–39

Contents lists available at ScienceDirect

Organic Electronics

journal homepage: www.elsevier.com/locate/orgel

Effective mobility in amorphous organic transistors: Influence of the width of the density of states

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ARTICLE INFO

Article history:
Received 17 July 2013
Received in revised form 2 September 2013
Accepted 6 October 2013
Available online 31 October 2013

Keywords:
Organic Thin Film Transistor (OTFT)
Modeling
Transport
Amorphous semiconductor
Temperature

ABSTRACT

The temperature dependence of poly(3-hexylthiophene-2,5-diyl) (P3HT)/polystyrene (PS) blend organic transistor current/voltage (*I–V*) characteristics has been experimentally and theoretically studied. The planar transistors, realized by drop casting the P3HT/PS ink, exhibit high mobilities (over 5×10^{-3} $cm^2\,V^{-1}\,s^{-1}$) and good overall characteristics. A transistor model accounting for transport mechanisms in disordered organic materials was used to fit the measured characteristics. Using a single set of parameters, the measured effective mobility versus gate bias, either increasing or decreasing with the gate bias depending on temperature, is well reproduced over a wide temperature range (130–343 K). A Gaussian density of states width of 0.045 eV was determined for this P3HT/PS blend. The transistor *I–V* characteristics are very well described considering disordered material properties within a self-consistent transistor model.

1. Introduction

The Organic Thin Film field effect Transistor (OTFT) is a key building block of a wide range of applications [1]. Despite improved overall performances, OTFTs still suffer from limitations ever delaying their use in commercial applications. On the one hand, reliability and reproducibility may not be at the required level. On the other hand, some device limitations are linked to charge carrier transport [2] and injection in organic materials [3]. It still appears mandatory to gain insight into some intrinsic physics of organic semiconductors.

A self-consistent OTFT current simulation software has been developed [4,5] implementing advanced mobility models, nonlinear injection model [6], and bias dependent contact resistances. The mobility model used in this study has been developed by Cottaar and co-authors [7]. It has been developed for disordered organic semiconductors where a Gaussian density of states and the mobility dependence on both temperature and carrier concentration are taken into account. The model is used to investigate the temperature behavior of OTFT electrical characteristics. In particular, the effective carrier mobility versus gate bias can be simulated and compared to experimental data, at various temperatures. Planar structure OTFTs have been fabricated by drop casting a P3HT/PS based ink and their characteristics were measured over a large temperature range (130–350 K). Their characteristics were then compared with the self-consistent model and material parameters could be determined. After a description of the device fabrication, the OTFTs electrical characteristics are presented. The transistor model is then briefly described, and comparison with experimental data is discussed based on material properties.

2. Sample preparation and electrical characterization

A polymer based ink has been developed for the fabrication of OTFTs by inkjet printing. The organic semiconductor is a blend of P3HT and polystyrene (PS) (1:5 ratio in weight) dissolved in tetralin. The PS is used to adjust the viscosity of the ink, while tetralin is chosen due to its high boiling point and its compatibility with multi-nozzles

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http://dx.doi.org/10.1016/j.orgel.2013.10.002

industrial print head. A set of P3HT/PS planar transistors has been fabricated by drop casting the P3HT based ink on bottom contact/bottom gate electrodes structures. The substrates consist of highly doped Si substrates, on which a 233 nm SiO_2 was thermally grown. Circular ITO/Au (10/30 nm) electrodes were patterned on the SiO_2, with a channel length of $L = 50\,\mu m$ and a channel width of $W = 1000\,\mu m$. Prior the P3HT deposition, the SiO_2 surface has been treated with hexamethyldisilazane (HMDS). The transistor current/voltage (I–V) characteristics have been measured under vacuum using an Agilent 5270B analyzer, at temperatures ranging from 130 K to 350 K. The measured transfer characteristics are shown in Fig. 1(a). Only very limited hysteresis is observed, except at high temperatures (343 K) where some interface traps seem to be activated. Below about 130 K the transistors became extremely resistive and could not be accurately measured. Also some residual gate leakage is responsible for noisy characteristics in the pA range and below. Experimental effective mobilities shown in Fig. 1(b) is extracted in saturated regime from the $\sqrt{I_{DS}}$ versus U_{GS} characteristic. The shape of the effective mobility versus gate bias varies with temperature, either increasing to decreasing. Maximum effective mobilities in excess of $5 \times 10^{-3}\ cm^2\ V^{-1}\ s^{-1}$ are obtained, slightly degraded compared to pure P3HT due to the presence of PS in the ink. The observed electrical characteristics are typical of an amorphous organic semiconductor: the measured maximum effective mobility is thermally activated, as shown in Fig. 2 (circle).

3. OTFT numerical model

In order to better understand the origin of the various effective mobility behaviors with temperature, an OTFT model was used to simulate the device characteristics. The OTFT drain current (I_{DS}) is calculated for a given couple of drain bias (U_{DS}) and gate bias (U_{GS}) using a numerical and distributed model. Drift and diffusion contributions are considered using the Einstein relation for the diffusion constant ($\mu/D = q/kT$). The numerical approach is basically the following: the drain current is calculated along the discretized channel (y axis) using the usual gradual channel approximation [8], the accumulated charge at each channel position being numerically calculated solving Poisson equation in the transverse direction (x axis). The organic semiconductor is considered intrinsic with a Gaussian density of states (DOS) typical of amorphous materials [9]. Only one type of carrier is considered mobile (here holes) in the channel, however both carriers are considered to contribute to the static equilibrium in the transverse Poisson equation resolution.

The mobility is carrier concentration and temperature dependent, following the approximation proposed in [7], to account for material disorder. This model is a parametric and analytic model which can be easily implemented in a numerical software. Several physical and fitting parameters have been optimized by Cottaar and co-authors to fit numerical results based on a transport master equation at low electric field. In particular, due to the hoping based transport model and to the Gaussian density of states, the carrier mobility strongly depends on the local carrier density. In the present distributed approach, the average mobility of each channel slice $\mu(y)$ is estimated from:

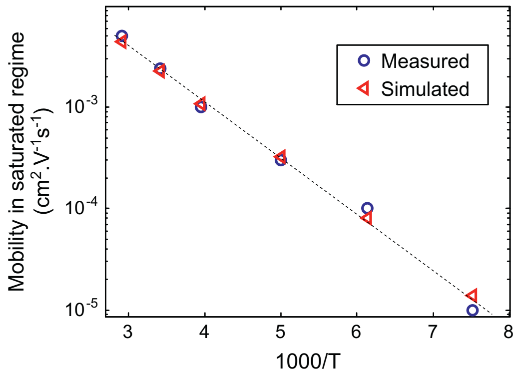

Fig. 2. Maximum measured (circle) and simulated (triangle) effective mobility in saturated regime at a drain–source bias of −60 V, for different temperature.

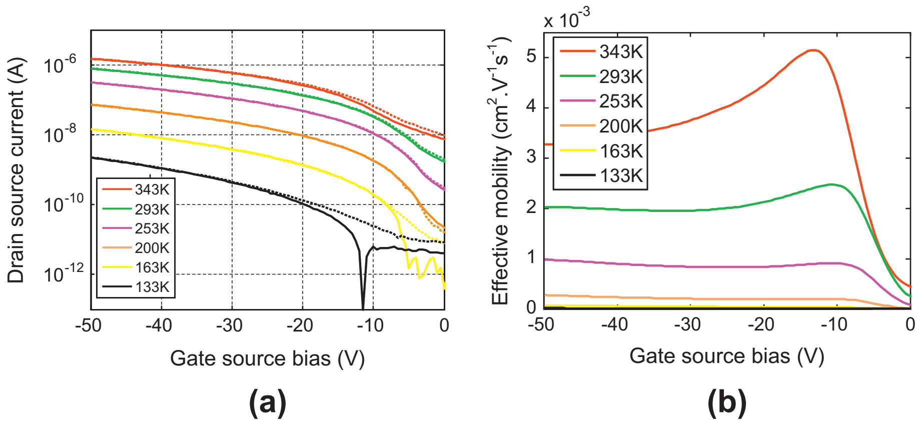

Fig. 1. P3HT/PS based transistor characteristics at various temperatures measured in saturated regime at $U_{DS} = -50$ V. (a) Transfer characteristics (plain lines: downward gate bias sweep/dashed lines: upward gate bias sweep). (b) Effective mobility versus gate bias.