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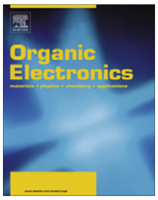

Analysis of contact effects in fully printed p-channel organic thin film transistors

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ABSTRACT

Contact effects have been analyzed in fully printed p-channel OTFTs based on a pentacene derivative as organic semiconductor and with Au source–drain contacts. In these devices, contact effects lead to an apparent decrease of the field effect mobility with decreasing L and to a failure of the gradual channel approximation (GCA) in reproducing the output characteristics. Experimental data have been reproduced by two-dimensional numerical simulations that included a Schottky barrier ($\Phi_b = 0.46$ eV) at both source and drain contacts and the effects of field-induced barrier lowering. The barrier lowering was found to be controlled by the Schottky effect for an electric field $E < 10^5$ V/cm, while for higher electric fields we found a stronger barrier lowering presumably due to other field-enhanced mechanisms. The analysis of numerical simulation results showed that three different operating regimes of the device can be identified: (1) low $|V_{ds}|$, where the channel and the Schottky diodes at both source and drain behave as gate voltage dependent resistors and the partition between channel resistance and contact resistance depends upon the gate bias; (2) intermediate V_{ds}, where the device characteristics are dominated by the reverse biased diode at the source contact, and (3) high $|V_{ds}|$, where pinch-off of the channel occurs at the drain end and the transistor takes control of the current. We show that these three regimes are a general feature of the device characteristics when Schottky source and drain contacts are present, and therefore the same analysis could be extended to TFTs with different semiconductor active layers.

1. Introduction

The electrical characteristics of organic thin film transistors (OTFTs) are frequently affected by contact effects [1–13], which can seriously influence the transistor performance. This is because the “parasitic” voltage drop at the contacts reduces the effective drain–source as well as gate-source bias voltages applied to the intrinsic channel of the transistor and, consequently, reduces the device current. Contact resistance appears to be strongly influenced by the device architecture and much higher values are typically observed in coplanar structures (or also known as bottom gate-bottom contact) than in staggered structures [3,4,7,8,12]. In the latter case, contact resistance appears to be constant with V_{ds}, as determined by the gated four point probe measurements [9] or by measurements on devices with different channel lengths [3], and to decrease for increasing $|V_{gs}|$ [3,9,10]. The gate bias dependence has been explained by considering the current crowding effect, which results in an increased contact area as the channel gets more and more accumulated [9,10], and space charge limited current in the bulk of the organic active layer [10]. An alternative approach to explain the

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gate bias dependence of the contact resistance in polycrystalline organic semiconductors based TFTs has been proposed by Vinciguerra et al. [11], who considered a combination of grain boundary trapping model, including an exponential density of trap states localized at these grain boundaries (Meyer-Neldel model), and Schottky contacts.

Two-dimensional (2D) numerical simulations have been shown to be a powerful tool to analyze contact effects in OTFTs [14–17]. In particular, the presence of Schottky barriers [14,16,17], trap state density [15] and field dependence of carrier mobility [14,16] have been shown to influence the contact characteristics. Recently, Kim et al. [17] have investigated the reason why charge transport in the channel appears to be not contact-electrode limited in staggered OTFTs whereas it is strongly contact-limited in coplanar OTFTs. They suggested that this difference originates from the continuity (staggered) or discontinuity (coplanar) of the carrier concentration at the channel ends [17]. Furthermore, Herasimovich et al. [15] have shown that nonlinearity in the output characteristics of staggered OTFTs may arise from the presence of a region with relatively high resistance separating the accumulated channel from the source and drain contacts. The high resistivity of this region could be due to either anisotropic mobility or to the presence of a high concentration of donor-like traps [15]. In the case of coplanar OTFTs Scheinert and Paasch [16] have shown that considering Schottky contacts can also induce nonlinearity, but for unrealistic parameters of the diodes at the source and drain. Vice versa, contact effects could be explained by the combination of Schottky contacts and field dependent mobility [14,16]. We note, however, that in the reported 2D numerical simulations a number of physical effects have been neglected: while in the work from Herasimovich et al. [15] the field dependence of the mobility has been neglected, in the works of Scheinert and Paasch [16] and Bolognesi et al. [14] the presence of trap states was neglected. In addition, in all reported 2D numerical simulations works including Schottky contacts [14–17] the field modulation of the barrier, induced by the Schottky effect, was not considered.

In this work we analyze by using 2D numerical simulations the electrical characteristics of fully printed p-channel staggered OTFTs to clarify the role of the contacts. Actually, we have recently reported anomalous increase of the contact resistance for increasing source–drain voltage in fully printed p-channel OTFTs, with field effect mobility up to 2 cm^2/V s [13]. The observed contact effects have been modeled by introducing at the source contact a reverse biased Schottky diode and a corresponding compact model was developed, allowing a precise reproduction of the transistor characteristics for different device geometries.

In order to gain a physical insight on the observed contact effects, we have introduced in the numerical simulations Schottky contacts at both source and drain electrodes, including barrier lowering induced by field enhanced mechanisms. We have also considered a trap state density determined by fitting the experimental characteristics of long channel devices. Finally, the effects of different barrier heights on the device characteristics is also analysed and presented.

2. Experimental

p-Channel OTFTs, with staggered top-gate configuration (see inset in Fig. 1), were fabricated at CEA-LITEN, using printing processes on PEN foils. The OTFTs have a multifinger structure with different channel lengths, L, (from 5 to 200 μm) and channel widths, W, (from 100 to 2000 μm). More details on devices fabrication can be found in Refs. [13,18].

Transfer characteristics measured at different source–drain voltages, V_{ds}, are reported in Fig. 1 for devices with channel lengths of 10 μm (Fig. 1a) and 200 μm (Fig. 1b). Output characteristics of device with $L = 10$ μm are shown in Fig. 2. The device transfer characteristics have been normalized to V_{ds} and in abscissa we used the difference between the gate voltage, V_{gs}, and $V_{ds}/2$. Assuming that the conventional square law theory applies, the different curves should superimpose, as in the case of the long channel device. This is not the case for the $L = 10$ μm device, showing for high $|V_{ds}|$ a substantial deviation from the expected behavior and suggesting a drastic drain current reduction due to contact resistance, R_s. The influence of R_s on electrical characteristics is also confirmed by the reduction of the field effect mobility, μ_{FE}, with decreasing device channel lengths observed in these devices [13] ($\mu_{FE} = 2$ and 1 cm^2/V s for $L = 200$ and 10 μm, respectively). On the other hand, as shown in [13], the output characteristics of these devices show a linear behavior at low $|V_{ds}|$, suggesting a low contact resistance, in agreement to what was already observed in staggered OTFTs [4]. However,

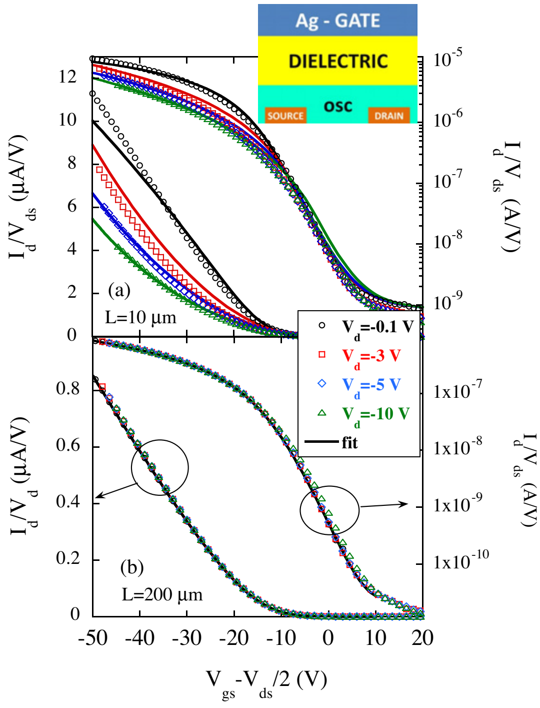

Fig. 1. Experimental (symbols) and simulated (solid lines) normalised transfer characteristics at different V_{ds} for a short channel device ($L = 10$ μm) (a) and for a long channel device ($L = 200$ μm) (b).