



Current spreading effects in fully printed p-channel organic thin film transistors with Schottky source–drain contacts

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ABSTRACT

Contact effects have been analyzed, by using numerical simulations, in fully printed p-channel OTFTs based on a pentacene derivative as organic semiconductor and with Au source/drain contacts. Considering source–drain Schottky contacts, with a barrier height of 0.46 eV, device characteristics can be perfectly reproduced. From the detailed analysis of the current density we have shown that current spreading occurs at the source contact, thus influencing the effective contact resistance. At low V_{ds} and for a given V_{gs} , the current is mainly injected from an extended source contact region and current spreading remains basically constant for increasing V_{ds} . However, by increasing V_{ds} the depletion layer of the Schottky contact expands and reaches the insulator–semiconductor interface, causing the pinch-off of the channel at the source end (V_{dsat1}). For $V_{ds} > V_{dsat1}$ the current injected from the edge of the source contact rapidly increases while the current injected from the remaining part of the source contact basically saturates. Current spreading shows a V_{gs} -dependence, since the contact injection area depends on the channel resistance and also barrier lowering of the Schottky source contact depends upon V_{gs} . The injected current from the edge of the source contact can be reproduced using the conventional diode current expression, assuming a constant value for the zero barrier lowering saturation current and considering a V_{gs} -dependent barrier lowering. The presented analysis clarifies the V_{gs} -dependence of the contact current–voltage characteristics and points out that the I – V contact characteristics cannot directly be related to a single diode characteristics. Indeed, the contact characteristics result from the combination of two rather different regimes: at low V_{ds} the current is injected from an extended source contact region with a current spreading related to V_{gs} , while for V_{ds} above the pinch-off of the channel at source end, the current is injected primarily from the edge of the source contact and is strongly enhanced by the barrier lowering.

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1. Introduction

The electrical characteristics of organic thin film transistors (OTFTs) are frequently affected by contact effects [1–10], 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 often to be constant with V_{ds} , as determined by the gated four point probe measurements [6] or by measurements on devices with different channel lengths [3], and to decrease for increasing $|V_{gs}|$ [3,6,7]. 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 [6,7], and space charge limited current in the bulk of the organic active layer [7]. An alternative approach to explain the gate bias

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dependence of the contact resistance in polycrystalline organic semiconductors based TFTs has been proposed by Vinciguerra et al. [8], 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 [11–17]. In particular, the presence of Schottky barriers [11,13–17], trap state density [12] and field dependence of carrier mobility [11,13] have been shown to influence the contact characteristics. Recent works have also shown that barrier lowering, induced by image force (Schottky effect) [15,16], as well as other field dependent mechanisms [15], can play an important role, determining a substantial enhancement in the carrier injection from the edge of the source contact, where the electric fields are more intense [15]. From the analysis of numerical simulation results we recently showed that three different operating regimes can be identified in the electrical characteristics of staggered top-gate OTFTs based on printed pentacene derivative with fluoropolymer gate dielectric [15]: (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. It should be pointed out that, due to the reverse bias operation of the Schottky diode at the source contact, the contact resistance was increasing with $|V_{ds}|$ [15]. This is in contrast with what observed by Richards and Sirringhaus in staggered top-gate poly-dioctylfluorene-co-bithiophene (F8T2) device with polystyrene dielectric, where the contact resistance was found to be $|V_{ds}|$ independent [6]. In general, contact resistivity, r_c , consists of two contributions: the injection resistivity due to the metal–semiconductor, r_{inj} , and the bulk resistivity of the semiconductor, r_{bulk} [6]. Therefore, the different observed V_{ds} -dependence of the contact resistance can be explained considering that when $r_{inj} \ll r_{bulk}$, contact resistance presents an ohmic behavior, as observed by Richards and Sirringhaus [6], while in the devices where $r_{inj} \gg r_{bulk}$, for non-ohmic injection resistivity, a V_{ds} -dependent contact resistance is expected [15].

It should be pointed out that, depending upon the relative values of channel (r_{ch}) and contact resistivity, the carrier injection takes place from different regions of the source contact. In particular, when $r_c \ll r_{ch}$, the injection will occur over a narrow area near the edge of the source contact, while, for $r_c \gg r_{ch}$, the whole geometric contact area will be used for injection. As a result, the current spreading at the contact results strongly dependent on the gate bias (V_{gs}), since r_{ch} is V_{gs} -dependent, and a schematic diagram is shown in Fig. 1. In the case of ohmic contact resistance, following the analysis proposed by Chiang et al. [18], it is possible to determine analytically a characteristic length, L_T , of the injecting contact region [6]. However, when the non-ohmic r_{inj} dominates the contact

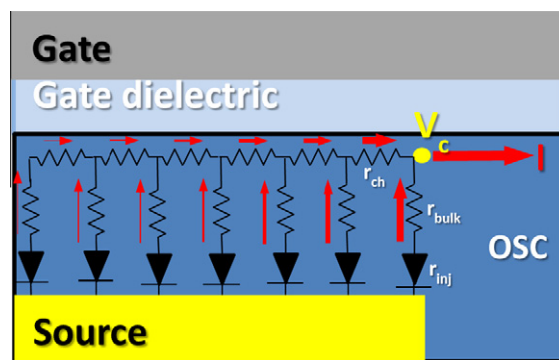


Fig. 1. Schematic of the device close to the source contact edge. Also indicated are the channel resistance, r_{ch} , the bulk resistance of the organic semiconductor, r_{bulk} , and the injection resistance due to the metal–semiconductor Schottky contact, r_{inj} .

resistance, the simple theory proposed by Chiang et al. [18] cannot be applied and, to our knowledge, an analysis of the current spreading in the presence of Schottky contacts is still lacking. In this work we have tried to clarify, by using 2D numerical simulations, the concomitant role of both current spreading and Schottky barrier on the contact effects in staggered OTFTs. In particular we have analyzed in more detail the first two operating regimes identified in ref [15].

2. Experimental

P-channel OTFTs, with staggered top-gate configuration, 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. [10] and [19].

Output characteristics measured at different gate voltages, V_{gs} , are reported in Fig. 2 for devices with channel lengths of 10 μm . In spite of the linear behavior of the output characteristics around $V_{ds} = 0$ V, we have shown, by using numerical simulations, that the device characteristics could be perfectly reproduced considering source–drain Schottky contacts [15]. By assuming that the total device resistance can be split into a contact resistance at the source region and the channel resistance, an approximation that has been validated by numerical simulations [15], it is possible to extract from the output characteristics shown in Fig. 2, by applying the method proposed in [10], the current–voltage characteristics of the source contact (see Fig. 3). As can be seen, the contact characteristics are clearly non-ohmic and look similar to those of a reverse biased diode, with a gate bias dependent reverse current and a field-dependent barrier height [10,15].

3. Numerical simulations

In order to elucidate the contact effects in our devices we analyzed the electrical characteristics by using the 2D numerical device analysis program DESSIS from Synopsys

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