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Contactless charge carrier mobility measurement in organic field-effect transistors

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A B S T R A C T

With the increasing performance of organic semiconductors, contact resistances become an almost fundamental problem, obstructing the accurate measurement of charge carrier mobilities. Here, a generally applicable method is presented to determine the true charge carrier mobility in an organic field-effect transistor (OFET). The method uses two additional finger-shaped gates that capacitively generate and probe an alternating current in the OFET channel. The time lag between drive and probe can directly be related to the mobility, as is shown experimentally and numerically. As the scheme does not require the injection or uptake of charges it is fundamentally insensitive to contact resistances. Particularly for ambipolar materials the true mobilities are found to be substantially larger than determined by conventional (direct current) schemes.

1. Introduction

The performance of organic field-effect transistors (OFET) increases remarkably, and an increasing number of organic semiconductors is being reported with a charge carrier mobility over that of a-Si, ~1 $cm^2/V\,s$ [1,2]. Especially n-type and ambipolar polymers recently made strong progression [3–8]. However, as the channel resistance decreases due to the increase of organic semiconductor mobilities, contact resistances often become the bottleneck for the total device performance [1,9,10]. Many strategies have been reported to decrease the contact resistance for either holes or electrons [1,10,11], using self-assembled monolayers [12,13], doping [14,15], interlayers [16,17], or by changing the device lay-out [9,18]. Contact resistance is an (even) more fundamental problem in ambipolar transistors, where both electrons and holes need to be injected [5,19]. The electron and hole injection barriers at any contact always sum up to the semiconductor band gap. Hence the injection barrier cannot be negligible for both holes and electrons simultaneously, leading to a contact resistance for at least one of the two charges. By using different contact materials for source and drain this problem can partially be solved, but for ease of fabrication it is preferred to have a single electrode material that is able to inject both types of charge carriers [20].

For research purposes one is often only interested in the transport properties of the semiconductor. The charge carrier mobility is then typically obtained by measuring the current in an OFET [21]. When the transistor suffers from contact resistance, a lower current and concomitantly a lower mobility is found. Correction for contact resistance

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is possible by estimating its value [22–26]. The most popular way to do so is by the transfer line method in which the resistance of OFETs as function of the channel length is measured. The extrapolated resistance at zero channel length is a measure for (twice) the contact resistance. This method however requires good device reproducibility [27,28].

In view of the above there is a clear need for a tool to determine the charge carrier mobility that is insensitive to contact resistance. Here we present such a technique. The basic idea is that an alternating current (AC) is capacitively generated and probed in an OFET channel. To this end two additional finger gates are placed near the accumulation layer. Conventional source and drain contacts are still required to fill the accumulation layer but do not need to absorb or inject any current and are therefore decoupled from the mobility measurement.

2. Materials and methods

2.1. Device fabrication

Devices were fabricated on cleaned glass substrates. The finger gates were created by evaporating 40 nm thick Au electrodes through a shadow mask substrate, preceded by a 2 nm Cr adhesion layer. Subsequently a 870 nm thick Cytop™ dielectric was applied by spin coating, followed by annealing for 30 min at 150 °C. On top of that, 40 nm Au source and drain electrodes were evaporated through a shadow mask. The active layer, poly[2,5-bis(2-hexyldecyl)-2,3,5,6-tetrahydro-3,6-dioxopyrrolo[3,4-c]pyrrole-1,4-diyl-alt-[2,2′-(1,4-phenylene)bisthiophene]-5,5′-diyl] (PDPPTPT), was applied by spin coating from a chloroform solution and annealed for 30 min at 200 °C [29,30]. Prior to spin coating, the Cytop™ dielectric required a treatment with a mild nitrogen plasma to enhance the semiconductor wetting. The gold work function was modified by either applying the semiconductor immediately after the plasma treatment, or first rinsing the gold electrodes with isopropanol. A second Cytop™ layer was spin coated on top of the stack and annealed at 150 °C for 30 min forming the gate dielectric. The thickness of the dielectric was 1.10 μm and 0.85 μm for the device with the solvent-rinsed contacts and non-rinsed contacts, resulting in a gate capacitance of $C_G = 1.85\ \mathrm{nC/cm^2}$ and $C_G = 2.4\ \mathrm{nC/cm^2}$, respectively. To finish the device, a 40 nm Au gate electrode was evaporated through a shadow mask. OFETs were measured in a high vacuum (10^{-5} mbar) probe station. Transfer characteristics were measured with a Keithley 4200 source-measure unit. Impedance spectroscopy was performed using a Solartron 1260A impedance analyzer in combination with a Keithley 2636 to apply the DC gate bias. The resulting lay-out of our device is shown in Fig. 1a.

2.2. AC characterization method

The device consists of a regular bottom-contact top-gate OFET, with the addition of a pair of finger gates positioned below the transistor channel. A dielectric separates the fingers from the transistor channel to ensure that their influence on the charges in the channel is entirely capacitive. The channel formed between the short distance between a pair of source and drain electrodes is used for simultaneous conventional direct-current (DC)-OFET characterization, whereas the long distance channel is used for AC characterization.

As shown in Fig. 1b an AC-bias is applied to one of the finger electrodes. The bias alternatingly pushes charges away from, or pulls charges towards the channel region above the finger gate, generating charge waves in the transistor channel. These charge waves are probed capacitively by the second finger gate. The time lag between the drive and probe signals can be related to the charge carrier mobility in the channel above the finger gates. In particular, by performing impedance spectroscopy on the fingers, a characteristic frequency f_c can be observed. Its value corresponds to the reciprocal transit time of charges moving between the fingers. We define the characteristic frequency of the finger-gate system as the frequency where the conductance divided by the frequency f peaks. The physical meaning of this quantity is the charge current per oscillation period flowing between the finger gate electrodes.

It is important that the modulating finger gates are sufficiently far away from the source and drain contacts such that the charge density modulations have damped out at the contacts. Then the contacts do not absorb or inject any charges and do not play a role in the AC measurement. With this condition fulfilled, this method differs fundamentally from conventional impedance measurements in which the source and drain do need to absorb and inject charge [31–35].

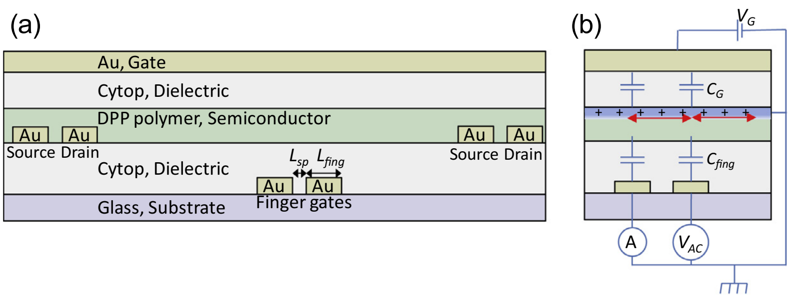

Fig. 1. (a) Cross section of the device lay-out. (b) Schematic operation principle of the finger gate structure in hole accumulation (i.e. at negative gate bias V_G). The accumulation layer is grounded via the source and drain.