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How small the contacts could be optimal for nanoscale organic transistors?

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ABSTRACT

We report on a study seeking an optimized contact configuration for organic transistors that minimizes contact effects but maintains smallest contact size. We begin with the bulk access resistance in staggered transistors which results from the charge transport through the organic semiconductor film. Bulk access resistance is an intrinsic contributor to the contact resistance which has been little understood due to lack of a reliable study tool. In this work, we utilize the inner transported power inside the semiconductor film as a medium to investigate the contact resistance and the relevant contact effects. We examine the influences of the organic film thickness (t_{SC}), the channel length (L), the underlying charge transport and various organic semiconductor materials with variable carrier mobility. A roughly optimal contact length (L_C) of $L_{C0} \approx 6t_{SC}$ is obtained. The results reveal that besides the device architecture the underlying charge transport should be also taken into account in designing organic transistors for practical application.

1. Introduction

Ohmic contact remains a big challenge to the new transistors using organic semiconductors [1], graphene [2], molybdenum disulfide (MoS_2) [3] and metal oxides [4]. Electrically poor contacts, which often manifest themselves as a high contact resistance (R_{sd}), severely degrade charge injection at the contact as well as charge transport in the channel [5]. These effects are being worsened in constant downscaling and should be solved for nano-size devices. Regarding organic field-effect transistors (OFETs), the staggered OFETs demonstrated small contact limitations [6–10], due to sizable charge injection area [6,11] and insensitivity to charge injection barrier [1,7,12], making them promising to nano integration for high speed operation [13]. Meanwhile, reports showed that a high parasitic capacitance induced by the large overlapping length (L_C, Fig. 1) between the source/drain contacts and the gate electrode adversely affects the cutoff frequency and the contact length or L_C needs to be minimized [13–15]. However, the advantages mentioned above will vanish if L_C decreases to zero [6]. Klauk and coworkers observed that the cutoff frequency (f_T) of an OFET could be expressed as [13,16]:

$$f_T \approx \frac{\mu_{eff}(V_G - V_T)}{2\pi L(L + 2L_C)}, \tag{1}$$

where μ_{eff} is the effective mobility, V_G and V_T are the gate and threshold voltage, respectively, and L is the channel length. It is clear from this equation that μ_{eff} and L_C have contradictory effects. Larger L_C favors the improvement of μ_{eff} [6,13] but becomes detrimental to f_T. On the other hand, higher L_C reduces contact resistance [13] but large contacts (sometimes as large as a millimeter) greatly

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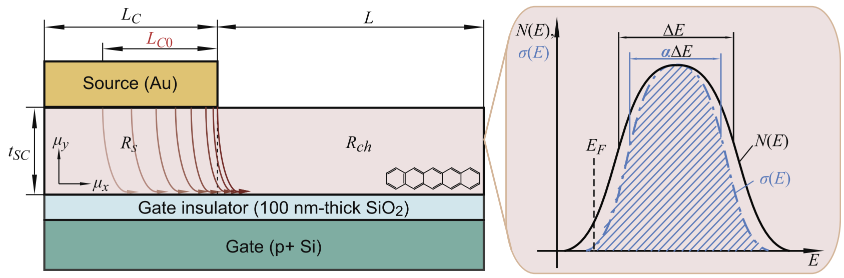

Fig. 1. (a) Pentacene OFET structure utilized in this study. For simplicity, only the source contact is shown. The OFET operates in linear regime at small drain voltage of −0.05 V. (b) Band structure where the DOS $N(E)$ is Gaussian distributed with a deviation of ΔE and the band conductivity $\sigma(E)$ has a smaller deviation of $\alpha\Delta E$. Higher energetic disorder will induce higher ΔE and more localized states in the band tails will decrease the corresponding conductivity, namely smaller α. For the following analyses, we set their typical values as ΔE = 0.1 eV and α = 0.85 for the common pentacene OFETs and different transport properties will be discussed later.

increase the device size and consume more contact material (e.g., Au). These two parallel considerations call for a better understanding of charge injection that may guide a search for the smallest contacts that maintain minimal contact effects, particularly important to nanoscale OFETs. In light of the lack of a reliable research tool for this issue, in this work we have applied a novel scheme to investigate the charge injection and the relevant effects. A quantitative analysis of the optimal L_C is provided which shows that L_C depends not only on the device architecture, but also on the underlying charge transport.

2. Method

A staggered pentacene OFET is taken as the object of this study, cf. Fig. 1. According to Joule's law, if the drain current I_D flowing through the organic semiconductor (OSC) film is known the contact and the channel resistances can be determined by integrating their corresponding local dissipated power over the whole contact/channel volume Ω as:

$$R = \frac{1}{I_D^2}\int_\Omega \rho J^2 d\Omega = \left(\frac{1}{V_D^2}\int_\Omega \sigma F^2 d\Omega\right)^{-1}, \qquad (2)$$

where ρ and J are the local resistivity and local current density, respectively. The second term is based on the local conductance with V_D being the drain voltage, σ and F being the local conductivity and local transport electric field, respectively. The solution to the Poisson equation, div[ε_{sc}·grad(ψ)] = $-q(n - n_0)$, provides the electrostatic potential (ψ) in the OSC film, corresponding to the local band bending, where ε_{sc} is the OSC permittivity and $-q(n - n_0)$ is the net OSC charge with q being the electron charge and n being the carrier concentration. The solution to the Laplace current continuity equation, div[σ·grad(ψ_n)] = 0, provides the quasi Fermi potential (ψ_n), corresponding to the local electric current flow, $J = \sigma F = -\sigma$·grad(ψ_n), in the OSC film. The two equations were solved using the finite element partial differential equation solver FlexPDE simultaneously [17]. The density of states (DOS) in the band is Gaussianly distributed in energy with a standard deviation ΔE [18], see Fig. 1. The macroscopic conductivity is calculated by summing microscopic conductivities over all band energies using the Kubo-Greenwood integral [19,20]. This total band conductivity is used to derive the dissipated power, cf. Eq. (2). The energy misalignment between the contact Fermi energy level and the OSC transporting band edge (i.e., the highest occupied molecular orbital, HOMO) is assumed to be negligible. Therefore, the contact resistance is not attributed to the charge injection barrier but rather due to the intrinsic component resulting from the charge transport through the OSC film at source and drain contacts [6,21]. Indeed, there have been many reports showing that the contact resistance of staggered OFETs is not sensitive to the charge injection barrier [1,7,12]. Yet, owing to a large gradient of charge density from the charge-rich contacts to the intrinsic OSC, a space charge region is formed inside the OSC bulk, inducing a built-in potential that maintains thermal equilibrium and limits charge injection rate [8]. Upon applying a negative gate bias, thermal equilibrium is broken as holes are injected and diffuse away from contacts into the OSC bulk. More details on the methodology can refer to Ref. [22].

A unique feature of this approach is that the contact resistance evaluation does not rely on knowing the specific current flow distribution. As the current flow is a vector and difficult to be exactly determined, the resultant contact analysis by means of either a resistance network or the standard device simulations would be not accurate enough for a full description of the complex charge injection [7,8,12,21,23–25]. The inner Joule's heating employed here offers an opportunity to overcome those restrictions and additionally the microscopic resistivity or conductivity are closely linked to the transport property, enabling us to inspect the impacts arising from the underlying charge transport that could not be achieved by using the conventional routines.

3. Results and discussions

3.1. Gate-voltage dependence

Fig. 2 shows the influences of the contact length (L_C) on the contact resistance ($R_{sd} = R_s + R_d$) and the channel resistance (R_{ch}). First, large L_C indeed decreases R_{sd} [13], but R_{ch} as well. The latter result indicates the alleviated contact limitation to channel transport achieved by providing larger injection area. Second, the strong dependence of R_{sd} on L_C is more observable at high V_G. This is in line with