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Contact engineering in organic field-effect transistors

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Organic field-effect transistors (OFETs) are promising for numerous potential applications but suffer from poor charge injection, such that their performance is severely limited. Recent efforts in lowering contact resistance have led to significantly improved field-effect mobility of OFETs, up to 100 times higher, as the results of careful choice of contact materials and/or chemical treatment of contact electrodes. Here we review the innovative developments of contact engineering and focus on the mechanisms behind them. Further improvement toward Ohmic contact can be expected along with the rapid advance in material research, which will also benefit other organic and electronic devices.

Introduction of contact injection

The injection problem

Newly synthesized organic semiconductors (OSCs) have demonstrated carrier mobilities of over 10 $cm^2/V\,s$ for the crystalline state and 2 $cm^2/V\,s$ for the amorphous state in organic field-effect transistors (OFETs) [1–5], approaching those of polycrystalline silicon metal–oxide–semiconductor FETs (Si MOSFETs). Such dramatic progress alleviates the bottleneck of the charge transport in OSCs but the need for improvement in contact injection properties remains. Conventional single-crystal Si MOSFETs can exhibit excellent contact properties (Ohmic contacts) since the charge injection is by tunneling from a metal contact to heavily doped silicon bulk, after injection the charge carriers can easily transport from the contact wells to the channel (bulk) as they are the same material, that is, silicon with different doping concentrations [6]. However, for new types of FETs, such as organic, metal oxide, and carbon-based FETs, the contact resistance (R_c) is not so good because the electrode–semiconductor junction consists of heterogeneous materials, that is, metal and semiconducting materials, which shows higher R_c values. For example, OFETs usually have an R_c value of 100 Ω cm as compared to that of Si MOSFETs where R_c is less than 0.1 Ω cm [7,8]. Therefore, the device performance is significantly limited by the poor charge injection and therefore a small enhancement of injection would lead to a considerable improvement of OFET performance. Some examples are shown in Table 1. Note that comparison between R_c values is only valid in the same example, since in different examples semiconductors, processing techniques, and device structure vary. For clarity, in this context we use '*field-effect mobility*' (μ_{FET}) to denote the mobility extracted from transfer characteristics measuring the OFET device performance (including device factors such as contact resistance), and use '*transport mobility*' (μ) to denote the mobility associated with transport property in semiconductor materials.

Contact injection barrier

The charge injection from metal/OSC junction has been described in terms of thermionic emission or tunneling mechanism. For both models, the current density in a metal/semiconductor diode is described as

$$J = J_0\left[\exp\left(\frac{qV_a}{kT}\right) - 1\right], \quad (1)$$

where V_a is the applied voltage on the semiconductor and J_0 is closely related to the Schottky barrier, φ_b, and depends on the properties of the metal/semiconductor junction. If not taking into account the image-lowering effect, the thermionic emission model (Richardson–Schottky model, Fig. 1a, left) gives

$$J_0 = J_{RS} = A^*T^2\exp\left(-\frac{q\varphi_b}{kT}\right), \quad (2)$$

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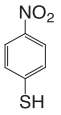
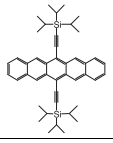
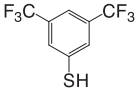
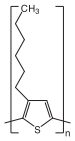
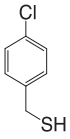
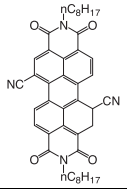
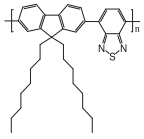
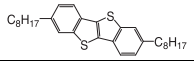
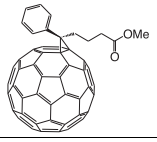
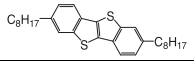
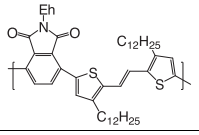
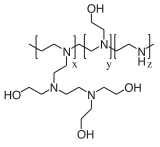
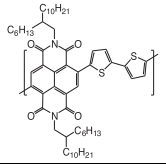
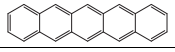
TABLE 1

Examples of contact engineering for OFETs. For contact resistance (R_c), field-effect mobility (μ_{FET}) and threshold voltage (V_{th}), the data inside and outside brackets are from unmodified electrodes and modified electrodes, respectively [extracted at the same gate voltage (V_g) and drain voltage (V_d) as in the references].

Contact engineering	Contact materials	Semiconductor (type of carriers)	φ_m (Au)	Device structure	R_c (kΩ cm)	μ_{FET} ($cm^2/(V\ s)$)	V_{th} (V)	Ref.
SAM (*p*-type)	NOTP/Au 	TIPS-Pentacene (p) 	4.84 (4.75)	TGBC	291 (998)	0.103 (0.047)	−6 (−9)	[9]
SAM (*p*-type)	BTFMBT/Au 	P3HT (p) 	5.8 (5.0)	TGBC	180 (610)	0.26 (0.16)	–	[10]
SAM (*n*-type)	4-Chlorobenzene-methanethiol/Au 	PDI-8CN2 (n) 	–	BGBC	32 (130)	0.10 (0.05)	10.6 (5.5)	[11]
SAM (ambipolar)	1DT/Au 	F8BT (ambipolar) 	4.0–4.2 (4.7–4.9)	TGBC	330 MΩ (560 MΩ) (p)/670 MΩ (2050 MΩ) (n)	0.0007 (0.0004) (p)/0.001 (0.0005) (n)	24 (32)/20 (30)	[12]
CIL (metal oxide, *p*-type)	MoO_3/Au	C8-BTBT (p) 	–	BGTC	10 (5000)[a]	2.3 (0.87)	−5 (−12)	[13]
CIL (metal oxide, *n*-type)	TiO_x/Au	$PC_{61}BM$ (n) 	–	BGTC	300 (15,000)	0.028 (∼0.001)	0 (5)	[14]
CIL (salts, *p*-type)	$FeCl_3$/Au	C8-BTBT (p) 	–	BGTC	8.8 (200)[b]	7.0 (3.4)	−10 (−24)	[15]
CIL (salts, *n*-type)	CsF/Au	PTVPhI-Eh (n) 	−4.1 to 4.2 (−4.7)	TGBC	5000 (1,200,000)[c]	0.26 (0.022)	44.27 (61.1)	[16]
CIL (polymer, *n*-type)	PEIE/Au 	P(NDI2OD-T2) (n) (N2200) 	3.90 (5.10)	TGBC	–	0.04 (0.1)	0.4 (4.5)	[17]
Carbon-based	Graphene	Pentacene (p) 	4.71 (4.46)	BGBC	560 (850)	0.4–1.01 (0.16–0.28)	–	[18]

[a] Read from Fig. 2 (at $V_g = 80$ V, $V_d = -3$ V) in the reference.
[b] Read from Fig. 2 (at $V_g = -40$ V, $V_d = -1$ V) in the reference.
[c] Read from Fig. 5 ($L = 10$ μm, $V_g = 60$ V, Eh = Ethylhexyl) in the reference.