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Nanomanufacturing — Key control characteristics

Part 5-1: Thin-film organic/nano electronic devices — Carrier transport measurements

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IEC TS 62607-5-1, which is a technical specification, has been prepared by IEC technical committee 113: Nanotechnology standardization for electrical and electronic products and systems.

The text of this technical specification is based on the following documents:

Enquiry draft	Report on voting
113/212/DTS	113/221/RVC

Full information on the voting for the approval of this technical specification can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 62607 series, published under the general title *Nanomanufacturing key control characteristics*, can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- transformed into an International standard,
- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
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A bilingual version of this publication may be issued at a later date.

INTRODUCTION

Organic/nano thin-film devices have many attractive features such as being light-weight and flexible, and having a low-cost, low-temperature fabrication process. Organic/nano electronic devices have been widely researched by academic institutions, research institutes, and materials and device industries. One of their possible applications is therefore expected to be in flexible and rollable devices. Many thin-film transistors based on organic semiconductor materials, called organic thin-film transistors (OTFTs), are expected to be mounted on organic electroluminescence display to drive each organic light-emitting diode pixel circuit. These OTFTs are also promising candidates for molecular nanoelectronics.

OTFTs show a relatively smaller carrier mobility (thin-film mobility: at most 10 cm^2/Vs, but usually less than 1 cm^2/Vs) compared with other thin-film transistors based on inorganic semiconductors (silicon, III-V compounds, metal oxides). Carrier transport properties such as thin-film mobility and thin-film carrier concentration in OTFTs are usually measured by simply applying the device physics of silicon metal-oxide-semiconductor transistors to OTFTs. Both the intrinsic bulk mobility of organic semiconductors and extrinsic effects such as contact resistance, carrier trap, interface, and surface state can limit thin-film mobility in OTFTs. Therefore, reliable methods of evaluating carrier transport properties for nanometer-scale thin-film materials have not yet been established and urgently need to be developed.

NANOMANUFACTURING – KEY CONTROL CHARACTERISTICS –

Part 5-1: Thin-film organic/nano electronic devices – Carrier transport measurements

1 Scope

This part of IEC 62607, which is a Technical Specification, provides a standardized sample structure for characterizing charge transport properties in thin-film organic/nano electronic devices and a format to report details of the structure which shall be provided with the measurement results. The standardized OTFT testing structure with a contact-area-limited doping can mitigate contact resistance and enable reliable measurement of the charge carrier mobility. The purpose of this Technical Specification is to provide test sample structures for determining the intrinsic charge transport properties of organic thin-film devices. The intention is to provide reliable materials information for OTFTs and to set guidelines for making test sample structures so that materials information is clear and consistent throughout the research community and industry.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60050 (all parts), *International Electrotechnical Vocabulary* (available at http://www.electropedia.org/)

IEC 62860, *Test methods for the characterization of organic transistors and materials*

3 Terms, definitions and abbreviations

For the purposes of this document, the terms and definitions given in IEC 60050-521 as well as the following apply.

3.1 Terms and definitions

3.1.1
organic thin-film transistor
OTFT
field-effect transistor that has a conduction channel made of thin films consisting of organic compounds

3.1.2
thin-film mobility
charge carrier mobility of the conduction channel (the semiconductor layer) in an OTFT

3.1.3
contact-area-limited doping
doping at around interface regions between the source and drain electrodes and the conduction channel in an OTFT

3.1.4
channel resistance
electrical resistance which comes from the conduction channel induced by applying gate voltages in a field-effect transistor

3.1.5
contact resistance
electrical resistance obtained by subtracting the channel resistance from the total electrical resistance between the source and drain electrodes in a field-effect transistor

Note 1 to entry: Main components of the contact resistance are electrical leads and carrier injection barriers at the interface between the source electrode and the semiconductor layer.

3.1.6
bottom-gate, bottom-contact device
field-effect transistor with the following structures:

– the gate electrode is located between the gate dielectric and the substrate;
– the source and drain electrodes are located directly on top of the substrate, and adjacent to the conduction channel-gate dielectric interface

3.1.7
bottom-gate, top-contact device
field-effect transistor with the following structures:

– the gate electrode is located between the gate dielectric and the substrate;
– the source and drain electrodes are located on top of the semiconductor layer

3.1.8
top-gate, bottom-contact device
field-effect transistor with the following structures:

– the gate electrode is located farthest away from the substrate;
– the gate dielectric is located between the gate electrode and the semiconductor layer;
– the source and drain electrodes are located directly on top of the substrate, and adjacent to the conduction channel-gate dielectric interface

3.1.9
top-gate, top-contact device
field-effect transistor with the following structures:

– the gate electrode is located farthest away from the substrate;
– the gate dielectric is located between the gate electrode and the semiconductor layer;
– the source and drain electrodes are located on top of the semiconductor layer

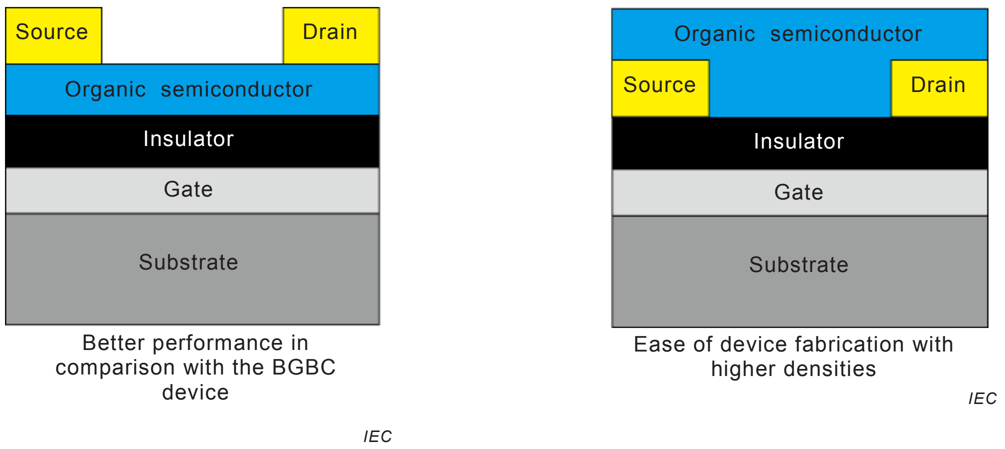
3.2 Symbols and abbreviated terms

OTFT	organic thin-film transistor
BGBC	bottom-gate, bottom-contact
BGTC	bottom-gate, top-contact
TGBC	top-gate, bottom-contact
TGTC	top-gate, top-contact
F4TCNQ	2,3,5,6-tetrafluoro-7,7,8,8-tetracyanoquinodimethane

4 Sample structures of OTFTs

4.1 Typical device structures of OTFTs

Several different device structures on OTFTs are possible, depending on the position of the source-drain and gate electrodes. Figure 1 illustrates two typical device structures: a bottom-gate, top-contact (BGTC) structure and a bottom-gate, bottom-contact (BGBC) structure. BGTC devices usually show better performance in comparison with BGBC devices. In comparison, the BGBC structure is more suitable for high-density device integration. However, high contact resistance is a common and serious problem in OTFTs regardless of the device structure, because the high contact resistance leads to the underestimation of the intrinsic field-effect channel mobility in OTFTs [1],[2][1].



a) **Bottom-gate, top-contact (BGTC)** b) **Bottom-gate, bottom-contact (BGBC)**

Figure 1 – Typical device structures of OTFTs

4.2 Contact-area-limited doping in OTFTs

Contact-area-limited doping is effective for increasing the drain current in OTFTs [2], [3], [4], [5], [6], [7]. In this type of doping, as shown in Figure 2, acceptor (or donor) doped layers are formed at the interface regions between the active semiconductor layer and the contact electrode. These doped layers cause a decrease in the contact resistance, resulting in an increase in the drain current.

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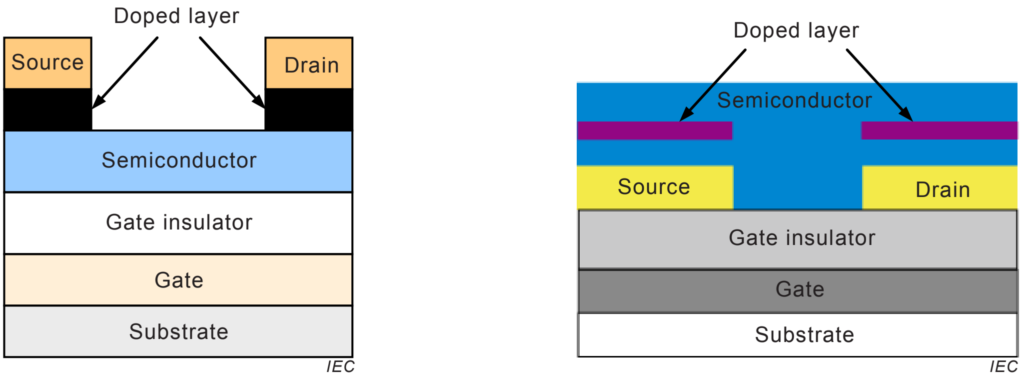
1 Figures in square brackets refer to the Bibliography.



a) BGTC transistor **b) BGBC transistor**

Figure 2 – Contact-area-limited doping in OTFTs

Contact-area-limited doping is a versatile method for improving the device performance of OTFTs. In other words, the effective thin-film mobility in the channel regions of OTFTs greatly depends on extrinsic effects such as structure and the electronic properties of the contact electrode area. Therefore, materials information on organic semiconductor films is not consistent throughout the research community and industry at present. This fact has led to this technical specification proposal for standard test sample structures. Namely, highly doped layers around contact electrodes are indispensable for reliably evaluating carrier mobility and concentration in organic semiconductor devices (see Figure 3).

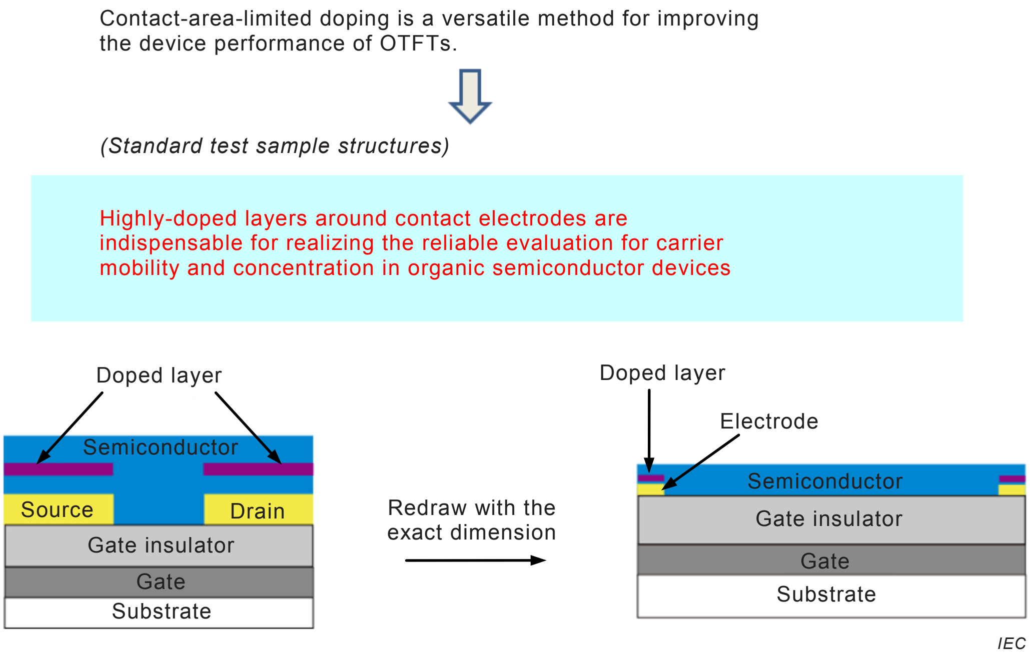


Figure 3 – Summary of this Technical Specification

5 Appropriate data format

A blank detail specification for OTFT test samples is an appropriate form for this Technical Specification (see Table 1). Items such as contact structure and contact electrode materials should be included in this Technical Specification.

Table 1 – Possible data format to be given together with carrier transport properties of OTFTs

Item	Specification
Contact structure	[ ] Bottom-gate, bottom-contact (BGBC) [ ] Bottom-gate, bottom-contact (BGTC) [ ] Top-gate, bottom-contact (TGBC) [ ] Top-gate, top-contact (TGTC)
Conditions of contact electrode Materials	Materials: [ ] Noble metals [ ] Transition metals [ ] Transparent conducting oxides [ ] Nano-carbon materials [ ] Conducting polymers [ ] Others Thickness of electrode: [ ] nm
Surface treatment of contact electrode	[ ] Doping with donor or acceptor materials (Carrier concentration of doped layers: [ ] cm^{-3} Thickness of doped layers: [ ] nm) [ ] Self-assembled monolayers (e.g. thiol, etc.) [ ] No surface treatment
Device parameters	Thin-film mobility: [ ] cm^2/Vs ([ ] Saturation regime [ ] Linear regime) Gate threshold voltage: [ ] V Subthreshold-swing: [ ] V/decade Contact resistance at gate voltages (V_g): [ ] ~ [ ] Ω ([ ] V < V_g < [ ] V) Channel resistance at gate voltages (V_g): [ ] ~ [ ] Ω ([ ] V < V_g < [ ] V) Employed measurement method for contact and channel resistances: [ ] 4 probe measurement [ ] Transmission line method [ ] Others Gate capacitance: [ ] nF/cm^2 Channel length and width (Length) /(Width): [ ] μm/ [ ] mm Thickness of active semiconductor layer: [ ] nm Carrier concentration of active semiconductor layer: [ ] cm^{-3}

Annex A
(informative)

Experimental studies on contact-area-limited doping in OTFTs

A.1 Contact-area-limited doping in bottom-gate, top-contact OTFTs

Clause A.1 describes an example of contact-area-limited p-type doping in bottom-gate, top-contact (BGTC) OTFTs in which pentacene was used as the p-type semiconductor material and 2,3,5,6-tetrafluoro-7,7,8,8-tetracyanoquinodimethane (F4TCNQ) as the acceptor dopant. Both materials are common and commercially available. The acceptor-doped layer was prepared by co-evaporation of pentacene and F4TCNQ. The evaporation rates of pentacene and F4TCNQ were 0,45 nm/min and 0,15 nm/min, respectively. The parameters of the device structure are shown in Figure A.1. In addition, BGTC devices without doped layers were also fabricated.

Firstly, deposition of the active pentacene layer (thickness: 50 nm) onto SiO_2 insulator was performed at the same time for these two samples. After that, for the device with the acceptor-doped layers, a 5-nm-thick doped layer was prepared by co-evaporation of pentacene and F4TCNQ using a shadow mask pattern for source-drain electrode fabrication, followed by the physical vapor deposition of a 25-nm-thick gold contact electrodes.

Transistor characteristics of the prepared devices were evaluated according to an appropriate IEC standard procedure (IEC 62860). The measurements were carried out under a vacuum of $1{,}0 \times 10^{-2}$ Pa. The effective field-effect mobility (μ_{eff}) and threshold voltage (V_{th}) were obtained from transfer characteristics (drain current (I_d) vs. gate voltage (V_g)) in the saturation regime according to the following equation;

$$I_d = WC_i \mu_{eff} (V_g - V_{th})^2 /(2L) \tag{1}$$

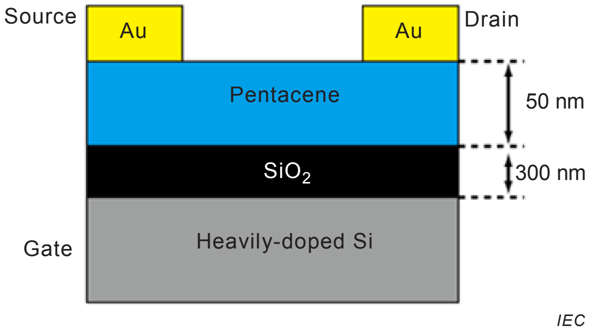
where

C_i is the gate capacitance per unit area;

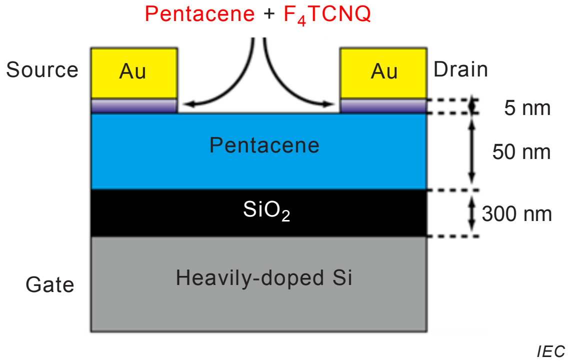
L is the channel length (50 μm);

W is the channel width (1 mm), respectively.

Here, the dielectric constant for SiO_2 was regarded to be 3,9.



a) Device structure of pentacene BGTC OTFT without carrier-doped layers



b) Device structure of pentacene BGTC OTFT with carrier-doped layers

Channel length (*L*)	50 µm
Channel width (*W*)	1 mm

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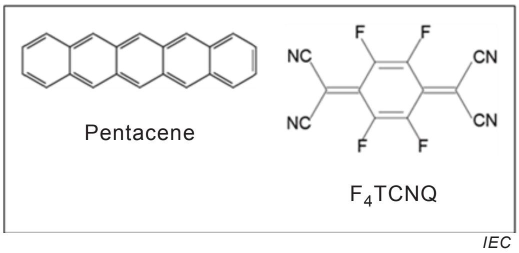
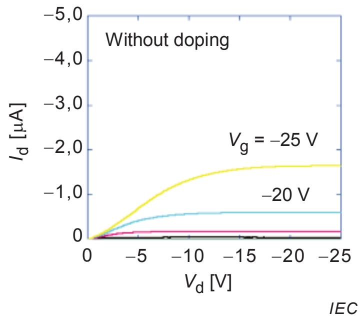
c) Channel length and width in pentacence BGTC OTFTs

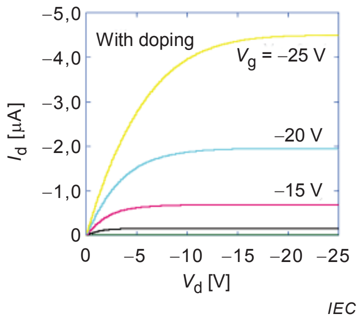


d) Molecular structures of pentacence and F4TCNQ molecules

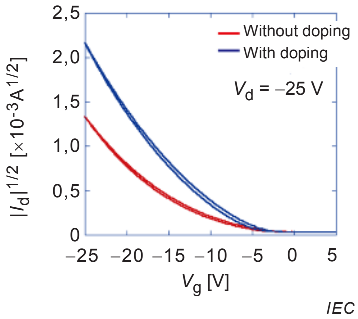
Figure A.1 – Sample preparation of bottom-gate, top-contact (BGTC) pentacene OTFTs using contact-area-limited doping



a) Drain current-drain voltage curves for pentacene BGTC OTFT without carrier-doped layers



b) Drain current-drain voltage curves for pentacene BGTC OTFT with carrier-doped layers



c) Drain current-gate voltage curves for both devices shown in Figures A.2a and A.2b

(V_g = –25 V)	Effective hole thin-film mobility [cm²/Vs]	Threshold voltage [V] obtained from plots in Figure A.2c
Without doping	0,12	–13,8
With doping	0,24	–11,9

Figure A.2 – Contact-area-limited doping effect in bottom-gate, top-contact (BGTC) pentacene OTFTs

The drain current-drain voltage curves and drain current-gate voltage curves are plotted in Figure A.2. The graphs show that the drain current for the device with the doped layer was larger than that for the undoped device. The effective field-effect mobility for hole doubled from 0,12 cm^2/Vs to 0,24 cm^2/Vs with contact-area-limited doping. This result confirms that the drain current was enhanced due to contact-area-limited doping in top-contact OTFTs.

A.2 Contact-area-limited doping in bottom-gate, bottom-contact OTFTs

Figure A.3 shows the sample preparation for a p-channel BGBC OTFT with doped layers. Pentacene and oligothiophene (α-sexithiophene) were used as p-type semiconductor materials and F4TCNQ as the acceptor dopant. All materials used here are common and commercially available. The acceptor-doped layer was prepared by co-evaporation of pentacene (or oligothiophene) and F4TCNQ. The parameters of the device structure are also shown in Figure A.3. The evaporation rates of pentacene, oligothiophene, and F4TCNQ were 0,45 nm/min, 0,59 nm/min, and 0,15 nm/min, respectively. The distance between the doped layer and the contact electrode was set to be 10 nm. In addition, BGBC devices without doped layers were also fabricated.

Firstly, a 25-nm-thick gold layer was vacuum deposited onto SiO_2 insulator through a shadow mask to form source-drain electrodes. The channel length (*L*) and width (*W*) were 50 μm and 1 mm, respectively. For devices with doped layers, a 10-nm-thick semiconductor layer was deposited onto the contact electrodes using the same shadow mask for electrode fabrication, followed by the deposition of a 5-nm-thick doped layer by co-evaporation of semiconductor and F4TCNQ molecules. Successively, after the removal of the shadow mask in air, deposition of the active semiconductor layer (thickness: 50 nm) was performed at the same time for undoped and doped BGBC devices.

Transistor characteristics of the prepared devices were evaluated according to an appropriate IEC standard procedure (see IEC 62860). The measurement procedure was similar to that described in Clause A.1.

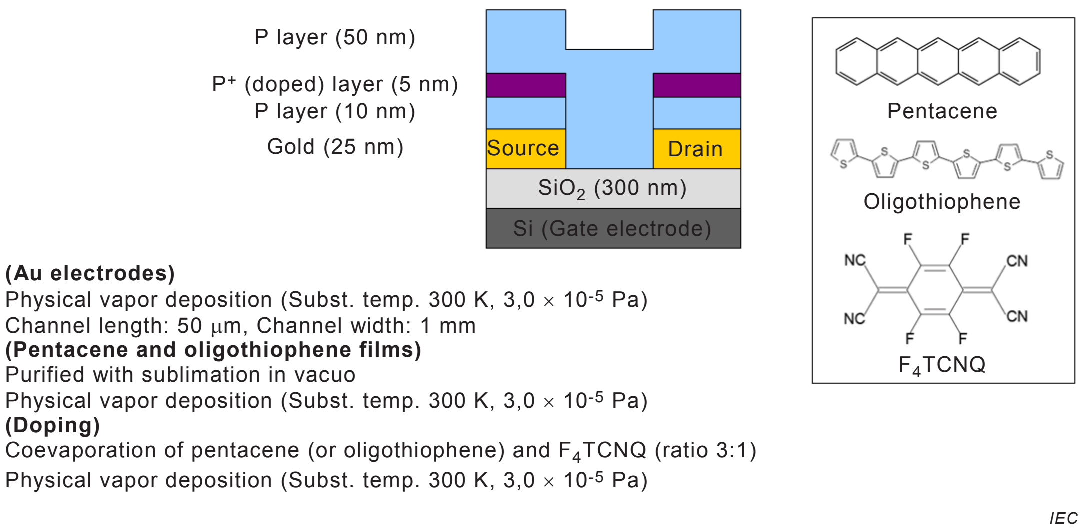
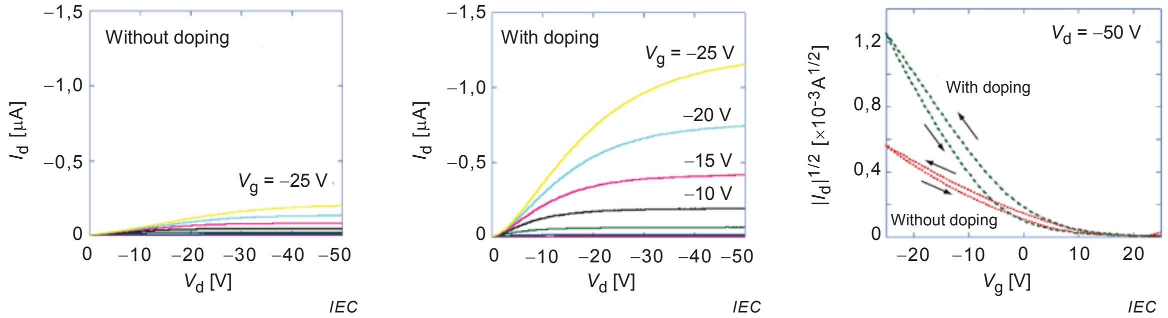


Figure A.3 – Sample preparation of bottom-gate, bottom-contact (BGBC) p-channel OTFTs using contact-area-limited doping

In bottom-gate, bottom-contact pentacene OTFTs, the drain current for the device with doped layers was larger than that for the undoped device, as shown in Figure A.4. The effective field-effect mobility for hole was raised from 0,003 cm^2/Vs to 0,024 cm^2/Vs with contact-area-limited doping. This result was also qualitatively confirmed with the device simulation [7].

In bottom-gate, bottom-contact oligothiophene OTFTs, the p-type doped layer increased the drain current, and the effective field-effect mobility for hole was raised from $1,4 \times 10^{-4}$ to $1,3 \times 10^{-3}$ cm^2/Vs with contact-area-limited doping, as shown in Figure A.5. This result suggests that the device structure with p-type doped layers is useful for improving the performance of bottom-contact p-channel OTFTs with an oligothiophene active layer as well as pentacene. The versatility of this contact-area-limited doping in bottom-contact OTFTs was experimentally confirmed.



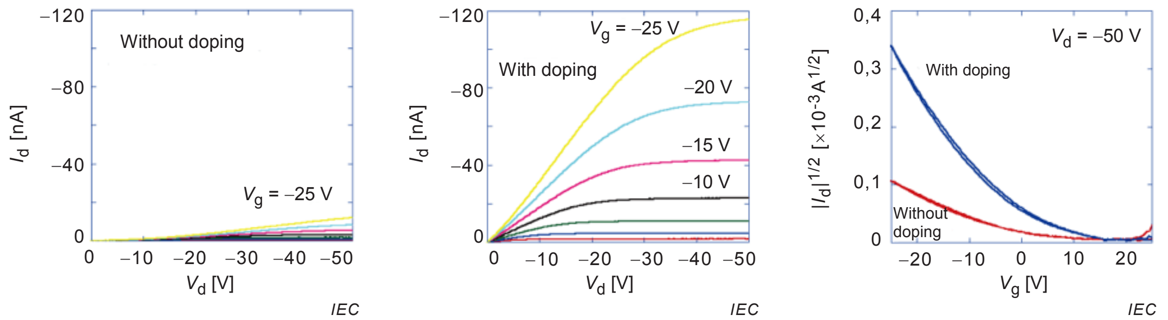
a) Drain current-drain voltage curves for pentacence BGBC OTFT without carrier-doped layers

b) Drain current-drain voltage curves for pentacence BGBC OTFT with carrier-doped layers

c) Drain current-gate voltage curves for both devices shown in Figures A.4a and A.4b

(V_g = –25 V)	Effective hole thin-film mobility [cm²/Vs]	Threshold voltage [V] obtained from plots in Figure A.4c
Without doping	3,0 × 10^{-3}	3,1
With doping	2,4 × 10^{-2}	–1,5

Figure A.4 – Contact-area-limited doping effect in bottom-gate, bottom-contact (BGBC) pentacene OTFTs



a) Drain current-drain voltage curves for oligothiophene BGBC OTFT without carrier-doped layers

b) Drain current-drain voltage curves for oligothiophene BGBC OTFT with carrier-doped layers

c) Drain current-gate voltage curves for both devices shown in Figures A.5a and A5b

(V_g = –25 V)	Effective hole thin-film mobility [cm²/Vs]	Threshold voltage [V] obtained from plots in Figure A.5c
Without doping	1,4 × 10^{-4}	0,1
With doping	1,3 × 10^{-3}	0,8

Figure A.5 – Contact-area-limited doping effect in bottom-gate, bottom-contact (BGBC) oligothiophene OTFTs

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