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TECHNICAL SPECIFICATION

Nanomanufacturing – Key control characteristics –
Part 5-3: Thin-film organic/nano electronic devices – Measurements of charge carrier concentration

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NANOMANUFACTURING – KEY CONTROL CHARACTERISTICS –

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IEC TS 62607-5-3, which is a Technical Specification, has been prepared by IEC technical committee 113: Nanotechnology for electrotechnical products and systems.

The text of this Technical Specification is based on the following documents:

Draft TS	Report on voting
113/477/DTS	113/523/RVDTS

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 TS 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 website 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- withdrawn,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
- amended.

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INTRODUCTION

Organic/nano thin-film devices are attracting much attention as promising candidates for light, low cost, flexible, and printable devices in large-area electronics applications. Recently, charge carrier doping techniques have been intensely studied and developed, in the same way as the mature silicon technologies. In organic light-emitting diodes (OLEDs) and organic thin-film transistors (OTFTs), which are typical organic/nano thin-film devices, carrier doping around contact electrode regions with molecular donor/acceptor dopants are often utilized to make ohmic-like contacts for the purpose of increasing electric current in the devices. While the great importance of carrier doping in organic/nano layers is well recognized, the carrier doping mechanisms have not been fully understood yet, and the evaluation method of charge carrier concentration in these materials has not been established.

Conventional representative methods for evaluating charge carrier concentrations (or dopant concentrations) and the type of charge carrier (electron or hole) in inorganic semiconductor materials are Hall-effect measurements and capacitance-voltage measurements. For example, the Hall-effect measurement based on the van der Pauw configuration enables one to get the above-mentioned physical parameters of the charge carrier in specimens with arbitrary shapes including thin-film structures. However, this versatile method cannot be utilized for higher resistance materials such as low-mobility organic semiconductors because of lower currents and sensitivities in the Hall effect. At the present time, the capacitance-voltage measurement based on metal/insulator/semiconductor structures is not applicable to highly-doped organic semiconductors that show some level of metallic behaviour. Therefore, standard methods and guidelines for measuring charge carrier concentration in organic semiconductor layers need to be developed.

NANOMANUFACTURING – KEY CONTROL CHARACTERISTICS –

Part 5-3: Thin-film organic/nano electronic devices – Measurements of charge carrier concentration

1 Scope

This part of IEC TS 62607, which is a Technical Specification, specifies sample structures for evaluating a wide range of charge carrier concentration in organic/nano materials. This specification is provided for both capacitance-voltage (C-V) measurements in metal/insulator/semiconductor stacking structures and Hall-effect measurements with the van der Pauw configuration. Criteria for choosing measurement methods of charge carrier concentration in organic semiconductor layers are also given in this document.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
doping
addition of impurities to a semiconductor to control hole or electron concentrations

Note 1 to entry: For organic semiconductors, not only atomic, but also molecular impurities are utilized.

Note 2 to entry: The added impurities are called "dopants".

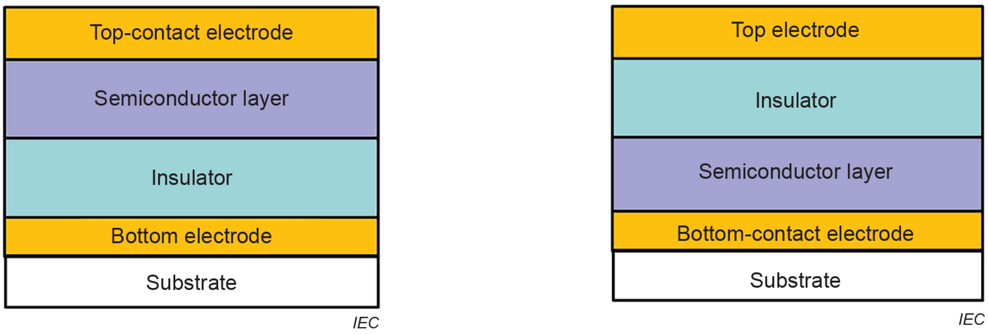
3.2
bottom-contact electrode
contact electrode located underneath the semiconductor layer to be tested

3.3
top-contact electrode
contact electrode located on top of the semiconductor layer to be tested

4 Sample structures

4.1 Metal/insulator/semiconductor (MIS) structure

Fabrication of a metal/insulator/semiconductor (MIS) structure as shown in Figure 1 is necessary for measuring a capacitance-voltage (C-V) curve in organic/nano semiconductor layers. This structure consists of a series capacitor of the insulator and a depletion region in the semiconductor layer.



a) Top-contact configuration **b) Bottom-contact configuration**

Figure 1 – Typical metal/insulator/semiconductor (MIS) structures

However, C-V measurements for MIS structures made of an identical semiconductor material provide various values of carrier concentration according to the difference in the sample structures (see Annex A, Clauses A.2, A.3 and A.4). Accordingly, the measurement of the carrier concentration with C-V measurements largely depends on the extrinsic effects derived from structure and electronic properties of the semiconductor layer itself and the metal/semiconductor interface region. Therefore, the following issues shall be considered for preparing MIS structures for reliable C-V measurements (Figure 2).

1) Quasi-ohmic contacts between the semiconductor layer and the metal electrode shall be formed. For example, contact doping is one of the practical techniques for this purpose.

2) For suppressing hysteresis phenomena in the measured C-V curves, the insulator in the MIS structure shall be as thin as possible, while maintaining good insulating properties.

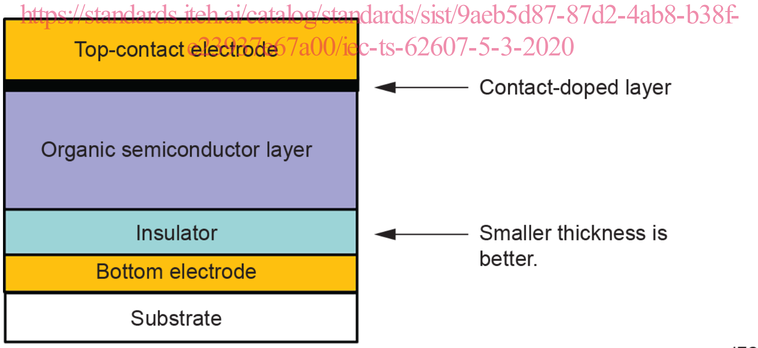
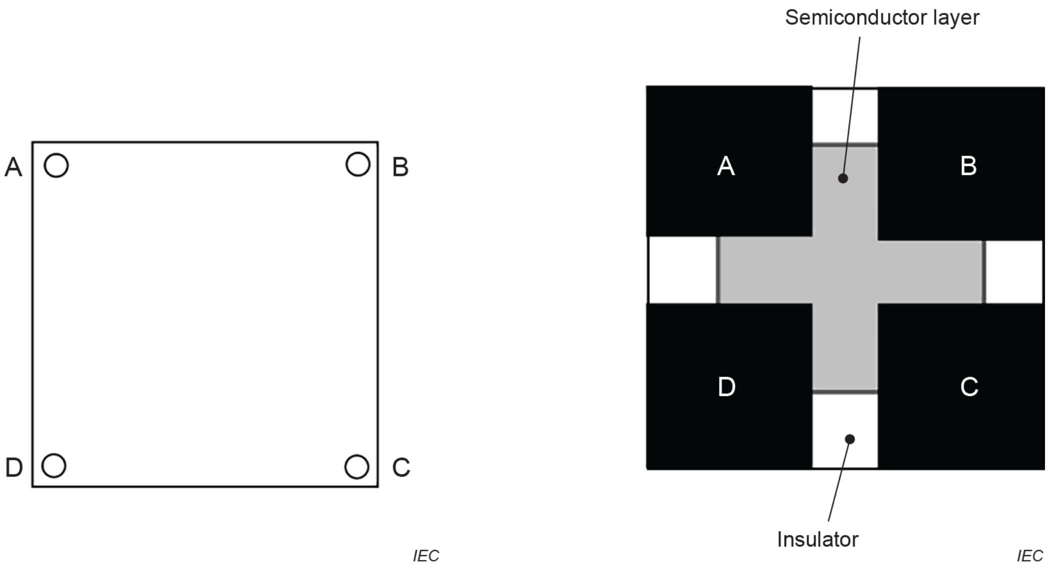


Figure 2 – An organic MIS structure favourable for capacitance-voltage measurements

4.2 Thin-film specimens with the van der Pauw configuration

Thin-film specimens with the van der Pauw configuration as shown in Figure 3 can be considered for Hall-effect measurement in highly-crystalline organic/nano materials.

Figure 3a) shows the conventional van der Pauw configuration with four point contacts at the corners of the square film specimens, where the distances between individual contacts are on a centimetre or millimetre scale. However, this versatile method cannot be applicable to higher resistance materials such as organic semiconductors because of lower currents and sensitivities in Hall effect. Therefore, an electrode structure with a micro-scale gap between diagonally opposite electrodes can be an alternative way for enabling Hall-effect measurement in an organic semiconductor layer as shown in Figure 3b). In this case, quasi-ohmic contacts between the semiconductor layer and the metal electrode shall be formed.



a) **Typical sample structure**

b) **Example of a sample structure with top-contact electrodes**

Figure 3 – Sample structures for Hall-effect measurement with the van der Pauw configuration

5 Criteria for choosing a method for measuring carrier concentration in organic semiconductor layers

Criteria for choosing a method for measuring carrier concentration in organic semiconductor layers are proposed as follows. Capacitance-voltage measurements are suitable for organic thin films with carrier mobilities lower than approximately 1 cm^2/Vs, while both Hall-effect measurements with van der Pauw configuration and capacitance-voltage measurements are considered to be available for organic thin films with carrier mobility higher than approximately 1 cm^2/Vs. The mobility of 1 cm^2/Vs has been regarded as the boundary value between band like transport region and hopping transport region [1][1]. The mobility can reach 1 cm^2/Vs to 10 cm^2/Vs in highly-crystalline thin films of some high-mobility organic semiconductors. However, values in the range of 10^{-5} cm^2/Vs to 10^{-1} cm^2/Vs in a large number of organic semiconductor thin films are not unusual because the mobility really depends on both the degree of order in molecular solids and extrinsic factors such as carrier traps and impurities [2].

6 Appropriate data formats

Examples of possible data formats for measurements of charge carrier concentrations in organic thin-film samples are given in Table 1 and Table 2. Items regarding measurement and sample conditions and results shall be included in these formats. Additionally, in the case of the Hall-effect measurements, it is highly recommended to show data plots on time variations of the measured Hall voltage against the polarity changes of the magnetic field.

[1] Numbers in square brackets refer to the Bibliography

Table 1 – Possible data format to be given together with carrier concentrations obtained with capacitance-voltage measurements

Item	Data
Measurement and sample conditions	Frequency of AC modulation voltage: [ ] Hz Amplitude of AC modulation voltage: [ ] V Sweep range of DC bias voltage: [ ] to [ ] V Measurement atmosphere: [ ] in a vacuum [ ] in an inert gas [ ] under ambient condition (relative humidity: [ ] %) Measurement temperature: [ ] K Active electrode area of the MIS structure: [ ] cm^2 Thickness of the active semiconductor: [ ] nm Dielectric constant of the active semiconductor: [ ]
Measurands	Majority carrier type: [ ] P-type [ ] N-type Carrier concentration: [ ] ± [ ] cm^{-3} Capacitance of insulator in the MIS structure: [ ] ± [ ] nF/cm^2 Hysteresis with DC bias sweep: [ ] No hysteresis [ ] With hysteresis (Hysteresis width: [ ] V)

Table 2 – Possible data format to be given together with carrier concentrations obtained with the Hall-effect measurements

Item	Data
Measurement and sample conditions	Kind of magnetic field: [ ] DC magnetic field [ ] AC magnetic field Amplitude of magnetic field: [ ] T Frequency of magnetic field: [ ] Hz (in the case of AC magnetic field) Amplitude of DC current: [ ] A Measurement atmosphere: [ ] in a vacuum [ ] in an inert gas [ ] under ambient condition (relative humidity: [ ] %) Measurement temperature: [ ] K Thickness of the active semiconductor: [ ] nm
Measurands	Majority carrier type: [ ] P-type [ ] N-type Carrier concentration: [ ] ± [ ] cm^{-3} Carrier mobility: [ ] ± [ ] cm^2/Vs Hall resistance: [ ] ± [ ] Ω Electrical resistivity: [ ] ± [ ] Ωcm