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TECHNICAL SPECIFICATION

colour inside

Nanomanufacturing – Key control characteristics – Part 6-16: Two-dimensional materials – Carrier concentration: Field effect transistor method

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NANOMANUFACTURING – KEY CONTROL CHARACTERISTICS –

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FOREWORD

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IEC TS 62607-6-16 has been prepared by IEC technical committee 113: Nanotechnology for electrotechnical products and systems. It is a Technical Specification.

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

Draft	Report on voting
113/679/DTS	113/698/RVDTS

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Specification is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

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.

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- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

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INTRODUCTION

Atomically thin 2D materials are expected to be used for future electrical sub-systems or electronic device applications. For these applications, the materials need to be doped with dopants to generate carriers. In contrast to 3D bulk materials, carrier concentrations in 2D materials are difficult to measure directly due to their limited thickness.

– Different from conventional 3D bulk materials in which doping effect is induced from activation of substitutional dopant atoms, the doping effect in 2D materials is mostly induced by generation of free carriers, for example electrons by using plasma treatment, chemical treatment, etc.

– In the 3D bulk materials, carrier concentration can be obtained by measuring concentration of dopant atoms under the assumption that both concentrations are the same. Therefore, it is possible to measure the doping concentration in 3D bulk materials using secondary ion mass spectroscopy (SIMS), which measures the concentration of dopant atoms, and using I-V or C-V characterization, which measures the concentration of free charge carriers such as electrons and holes [1][1].

– In contrast, in the 2D materials, carrier concentration needs to be measured for carriers such as electrons and holes which are induced from external means such as plasma treatment or chemical treatment.

For this reason, a standard method to determine the carrier concentration needs to be established for 2D materials.

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[1] Numbers in square brackets refer to the Bibliography.

NANOMANUFACTURING –
KEY CONTROL CHARACTERISTICS –

Part 6-16: Two-dimensional materials –
Carrier concentration: Field effect transistor method

1 Scope

This part of IEC TS 62607 establishes a standardized method to determine the key control characteristic

- carrier concentration

for semiconducting two-dimensional materials by the

- field effect transistor (FET) method.

For semiconducting two-dimensional materials, the carrier concentration is evaluated using a field effect transistor (FET) test by a measurement of the voltage shift obtained from transfer curve upon doping process. The FET test structure consists of three terminals of source, drain, and gate where voltage is applied to induce the transistor action. Transfer curves are obtained by measuring drain current while applying varied gate voltage and constant drain voltage with respect to the source which is grounded.

- The method is applicable to semiconducting two-dimensional materials with a bandgap like that in transition metal dichalcogenides (MoS_2, $MoTe_2$, WS_2, WSe_2, etc.) and black phosphorous. Pristine graphene shows semi-metallic characteristics without bandgap, and therefore this method is not applicable to pristine graphene. However, it can be used for other graphenes with bandgap (for example, semiconducting graphene oxide).
- It is likely that the measurement results will help to qualify technologies if they are usable for future electrical sub-systems or electronic device applications.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

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 General terms

3.1.1

key control characteristic

KCC

key performance indicator

material property or intermediate product characteristic which can affect safety or compliance with regulations, fit, function, performance, quality, reliability or subsequent processing of the final product

Note 1 to entry: The measurement of a key control characteristic is described in a standardized measurement procedure with known accuracy and precision.

Note 2 to entry: It is possible to define more than one measurement method for a key control characteristic if the correlation of the results is well-defined and known.

3.1.2

bilayer graphene

2LG

two-dimensional material consisting of two well-defined stacked graphene layers

Note 1 to entry: If the stacking registry is known, it can be specified separately, for example, as "Bernal stacked bilayer graphene".

[SOURCE: ISO/TS 80004-13:2017 [2], 3.1.2.6]

3.1.3

few-layer graphene

FLG

two-dimensional material consisting of three to ten well-defined stacked graphene layers

[SOURCE: ISO/TS 80004-13:2017 [2], 3.1.2.10]

3.1.4

two-dimensional material

2D material

material, consisting of one or several layers with the atoms in each layer strongly bonded to neighbouring atoms in the same layer, which has one dimension, its thickness, in the nanoscale or smaller, and the other two dimensions generally at larger scales

Note 1 to entry: The number of layers when a two-dimensional material becomes a bulk material varies depending on both the material being measured and its properties. In the case of graphene layers, it is a two-dimensional material up to ten layers thick for electrical measurements, beyond which the electrical properties of the material are not distinct from those for the bulk (also known as graphite).

Note 2 to entry: Interlayer bonding is distinct from and weaker than intralayer bonding.

Note 3 to entry: Each layer may contain more than one element.

Note 4 to entry: A two-dimensional material can be a nanoplate.

[SOURCE ISO/TS 80004-13:2017 [2], 3.1.1.1]

3.2 Key control characteristics measured in accordance with this document

3.2.1

2D carrier concentration

characteristic described by the areal density of electrons or holes free to move in two dimensions due to the atomical thinness of 2D materials that restricts the movement of the carriers in the third direction

Note 1 to entry: The unit of 2D carrier concentration is [cm^{-2}]

Note 2 to entry: In general, increased doping leads to increased conductivity due to the higher concentration of the charge carriers. Carrier density in conventional semiconductors is usually tuned with substitutional doping. However, substitutional doping is very difficult in 2D materials due to their nanometre-scale thickness. Generally, in conventional semiconductors, the doping concentration at room temperature is assumed to be the same as the free carrier concentration because free carriers such as electrons or holes are generated from fully ionized dopant atoms. Therefore, doping concentration in bulk semiconductors can be estimated by various methods, e.g. SIMS, X-ray photoelectron spectroscopy (XPS), and I−V (C−V) characterization. By contrast, doping in 2D materials is induced mainly by electrostatic gating or charge transfer and therefore doping concentration in 2D materials needs to be determined by electrical characterization. [3]

3.3 Terms related to the measurement method

3.3.1
field effect transistor
FET
transistor in which the voltage on one terminal (gate) creates a field that allows or disallows conduction between the other two terminals (source and drain)

Note 1 to entry: The carrier concentration of a semiconductor can be modulated by electrostatic gating in an FET configuration. In the FET, two metal electrodes (source and drain, S/D) formed on the sample are used to provide driving force for the lateral current conduction, while the third electrode (gate, G) is used to modulate the current conduction on the sample surface across a gate dielectric material.

3.3.2
transfer curve
graph that provides corresponding output current values for each possible voltage input to an electronic or control system component

Note 1 to entry: Transfer curves are obtained by measuring drain current (I_D) as a function of gate voltage (V_G) at constant drain voltage (V_D).

3.3.3
charge neutral point
point at which the electron current is equal to hole current in semiconductors

4 General

4.1 Measurement principle

Doping concentration, which is equivalent to free carrier concentration, can be determined by shift of charge neutral point in transfer curves (drain current as a function of gate voltage). This method requires to use a transistor, more specifically a FET, and works well for semiconducting materials.

4.2 Sample preparation method

4.2.1 Sample preparation

2D materials, which are obtained mostly through micromechanical exfoliation or chemical vapour deposition, are typically deposited on Si substrates covered with thermally grown SiO_2 film. Raman spectroscopy and XPS can be performed to identify their chemical components and to analyse defects. Heterostructure is prepared by stacking 2D materials.

4.2.2 Fabrication of FET

A typical example for substrates to be used for 2D materials is

- silica on silicon (SiO_2 on Si).

The bottom gate electrode can consist of

- highly doped Si substrate wafers used for electrical back gating, underneath the SiO_2.