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TECHNICAL SPECIFICATION

colour inside

Nanomanufacturing – Key control characteristics – Part 6-5: Graphene-based materials – Contact resistance and sheet resistance: transmission line measurement

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IEC TS 62607-6-5 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
113/677/DTS	113/709/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.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

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- withdrawn,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

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INTRODUCTION

Technical Specifications for contact resistance and sheet resistance of two-dimensional materials provide a proper definition of contact resistance and sheet resistance measurement and an electrical characterization of two-dimensional materials. This document includes recommended conditions for a sample preparation and recommended method to measure contact resistance and sheet resistance of two-dimensional materials under test in the referenced background research results. Here, the transmission line measurement (TLM) is used which had been used to measure both contact resistance and sheet resistance for conventional bulk semiconductor devices including silicon devices. TLM devices are formed with various spacings between contacts from which contact resistance and sheet resistance are determined from voltage measured. Thickness of the atomic thin 2D materials cannot be defined clearly when the layers are ultrathin near monolayer, and therefore it is difficult to express the thickness-dependent electronic resistivities of the devices fabricated by using 2D materials. TLM is used conveniently to determine contact resistance and sheet resistance of 2D materials since it does not require thickness of tested materials to be included in the calculation procedure.

The objectives of this document are to

a) define the contact resistance and sheet resistance of two-dimensional materials;

b) specify the methodology for contact resistance and sheet resistance measurements of two-dimensional materials using transmission line measurement (TLM);

c) provide a contact formation method for two-dimensional materials with ohmic contact property which is an essential prerequisite;

d) establish units for the quantitative characteristics of contact resistance and sheet resistance for two-dimensional materials;

e) provide relevant case studies;

f) provide relevant references.

This document is meant to be a general document that can be applied to two-dimensional materials and their applications. It is the intent of this document to be compatible with and work in conjunction with the performance standards defined in the IEC TS 62607 series.

NANOMANUFACTURING – KEY CONTROL CHARACTERISTICS –

Part 6-5: Graphene-based materials – Contact resistance and sheet resistance: transmission line measurement

1 Scope

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

- contact resistance, and
- sheet resistance

for graphene-based materials and other two-dimensional materials by a

- transmission line measurement.

The method uses test structures applied to the 2D material by photolithographic methods consisting of several metal electrodes with increasing spacing between the electrodes. By a measurement of the voltage drop between different pairs of electrodes, sheet resistance and contact resistance can be calculated.

- The method can be applied to any other two-dimensional materials which are subject to electrical metal contact on top of the materials.
- The method provides accurate and reproducible results, if the electrical contact formed between the two-dimensional material and the metal electrodes provides ohmic contact property.

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 General terms

3.1.1
detail specification
DS
specification based on a blank detail specification with assigned values and attributes

Note 1 to entry: The properties listed in the detail specification are usually a subset of the key control characteristics listed in the relevant blank detail specification. The industrial partners define only those properties which are required for the intended application.

Note 2 to entry: Detail specifications are defined by the industrial partners. Standards development organizations will be involved only if there is a general need for a detail specification in an industrial sector.

Note 3 to entry: The industrial partners can define additional key control characteristics if they are not listed in the blank detail specification.

3.1.2
graphene
graphene layer
single-layer graphene
monolayer graphene
single layer of carbon atoms with each atom bound to three neighbours in a honeycomb structure

Note 1 to entry: It is an important building block of many carbon nano-objects.

Note 2 to entry: As graphene is a single layer, it is also sometimes called monolayer graphene or single-layer graphene and abbreviated as 1LG to distinguish it from bilayer graphene (2LG) and few-layer graphene (FLG).

Note 3 to entry: Graphene has edges and can have defects and grain boundaries where the bonding is disrupted.

[SOURCE: ISO/TS 80004-13:2017, 3.1.2.1]

3.1.3
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, 3.1.2.6]

3.1.4
few-layer graphene
FLG
two-dimensional material consisting of three to ten well-defined stacked graphene layers

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

3.1.5
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 10 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 can contain more than one element.

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

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

3.2 Key control characteristics

3.2.1
key control characteristic
KCC
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.

3.2.2
sheet resistance
measure of the resistance of a thin film that is nominally uniform in thickness

Note 1 to entry: Sheet resistance can be measured together with contact resistance by TLM for 2D materials, as shown in Figure 2.

Note 2 to entry: Sheet resistance is one of a material's properties. The SI unit of measure of sheet resistance is the ohm per square (Ω/sq.).

3.2.3
contact resistance
measure of the contribution of the contacting interfaces to the total resistance of thin films that are nominally uniform in thickness

Note 1 to entry: Contact resistance can be measured together with sheet resistance by TLM for 2D materials, as shown in Figure 2.

Note 2 to entry: Contact resistance is a property that exists between a metal and a semiconducting (or conducting) material. Contacts need to supply necessary electrical current.

[SOURCE: Schroder [1], Pages 127, 131]

3.3 Terms related to the measurement method

3.3.1
transfer length
L_T
measuring distance over which most of the current flows from a semiconductor (or conducting material) into a metal or from a metal into a semiconductor (or conducting material)

[SOURCE: Schroder [1], Page 140]

3.3.2
transmission line measurement
TLM
measuring method to determine sheet resistance of a layer and contact resistance between a layer and an applied electrode by the formation of a set of electrodes and a measurement of the voltage drop between the electrodes

Note 1 to entry: In some cases, TLM is used as abbreviation for transfer length measurement, but this represents the same technique as the transmission line measurement.

[SOURCE: Schroder [1], Pages 139-141]