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TECHNICAL SPECIFICATION

colour inside

Nanomanufacturing – Key control characteristics – Part 6-7: Graphene – Sheet resistance: van der Pauw method

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CONTENTS

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NANOMANUFACTURING –
KEY CONTROL CHARACTERISTICS –

Part 6-7: Graphene – Sheet resistance: van der Pauw method

FOREWORD

IEC TS 62607-6-7 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
113/682/DTS	113/713/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 of 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- withdrawn,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

Graphene is a single layer of carbon atoms arranged in a honeycomb lattice. Graphene has shown many outstanding properties, among which is a high electrical conductivity. Nowadays graphene can be easily grown and transferred on large area (cm^2 to even m^2) and even roll-to-roll supports using chemical vapour deposition (CVD) techniques. This is already enabling its commercial applications in electrotechnical products.

Electrical conductivity of graphene samples can depend on many factors: structural quality, contamination, coupling with the physical support used for a given application to name a few. On practical grounds, sheet resistance is a quantity which can be used as global measure of the local conductivity of a sample with finite geometrical dimensions. In order to check the reproducibility of the electrical properties of graphene, the sheet resistance is clearly a key control characteristic for this material.

The van der Pauw method [1][1] allows the measurement of the sheet resistance of samples of arbitrary shape, with isotropic conductivity and uniform carrier density by performing a pair of four-terminal resistance measurements with electrical contacts placed at arbitrary positions on the sample's perimeter. The method is fast (it takes a few minutes) and easy to implement, since many commercial fixtures are available.

The four-terminal resistance measurements required to apply the method allow to minimize the effect of the contact resistance that appears between graphene and the measurement probes.

The van der Pauw method does not provide any spatial resolution in principle, but considerations about real samples' conductivity uniformity can be made.

In this document it is explained how to specifically apply the van der Pauw method on chemical vapour deposited graphene on rigid insulating support and perform a reliable estimation of the sample sheet resistance also considering the non-ideal nature of commercial graphene.

1 Numbers in square brackets refer to the Bibliography.

NANOMANUFACTURING – KEY CONTROL CHARACTERISTICS –

Part 6-7: Graphene – Sheet resistance: van der Pauw method

1 Scope

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

- sheet resistance R_S [measured in ohm per square (Ω/sq)],

by the

- van der Pauw method, vdP.

The sheet resistance R_S is derived by measurements of four-terminal electrical resistance performed on four electrical contacts placed on the boundary of the planar sample and calculated with a mathematical expression involving the two resistance measurements.

- The measurement range for R_S of the graphene samples with the method described in this document goes from 10^{-2} Ω/sq to 10^4 Ω/sq.
- The method is applicable for CVD graphene provided it is transferred to quartz substrates or other insulating materials (quartz, SiO_2 on Si), as well as graphene grown from silicon carbide.
- The method is complementary to the in-line four-point-probe method (4PP, IEC 62607-6-8) for what concerns the measurement of the sheet resistance and can be applied when it is possible to reliably place contacts on the sample boundary, avoiding the sample being scratched by the 4PP.
- The outcome of the van der Pauw method is independent of the contact position provided the sample is uniform, which is typically not true for graphene at this stage. This document considers the case of samples with non-strictly uniform conductivity distribution and suggests a way to consider the sample inhomogeneity as a component of the uncertainty on R_S.

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
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]

3.1.2
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, 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, 3.1.2.10]

3.2
key control characteristic
KCC
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.

[SOURCE: IEC TS 62565-1:2023, 3.1]

3.3
blank detail specification
BDS
structured generic specification providing a comprehensive set of key control characteristics which are needed to describe a specific product without assigning specific values or attributes

Note 1 to entry: Examples of nano-enabled products are: nanocomposites and nano-subassemblies.

Note 2 to entry: Blank detail specifications are intended to be used by industrial users to prepare their detail specifications used in bilateral procurement contracts. A blank detail specification facilitates the comparison and benchmarking of different materials. Furthermore, a standardized format makes procurement more efficient and more error robust.

[SOURCE: IEC TS 62565-1:2023, 3.2]

3.4
detail specification
DS
specification based on a blank detail specification with assigned values and attributes

Note 1 to entry: The characteristics 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 characteristics 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 may define additional key control characteristics if they are not listed in the blank detail specification.

[SOURCE: IEC TS 62565-1:2023, 3.3]

3.5 Key control characteristics measured in accordance with this standard

3.5.1
sheet resistance
R_S
electrical resistance of a conductor with a square shape (width equal to length) and thickness significantly smaller than the lateral dimensions (thickness much less than width and length)

Note 1 to entry: There is no definition of the unit ohm per square (Ω/sq) in the International System of units (SI). Nevertheless, R_S is a normalized quantity, in which the symbol represents the SI ohm. So there is no ambiguity concerning the traceability of measurements of R_S to the SI, provided the measurements are performed with calibrated instrumentation.

[SOURCE: IEC TS 61836:2007, 3.4.79, modified – The entry has been adapted to this document.]

3.5.2
drift mobility
μ
<of a charge carrier> quotient of the modulus of the mean velocity of the charge carriers in the direction of an electric field by the modulus of the field strength

Note 1 to entry: The SI unit of mobility is $cm^2/V\ s$.

Note 2 to entry: The drift mobility is here considered to be the fundamental, intrinsic (local) property. The Hall and field effect mobility are then the extrinsic (sample) electrical measurements, carried out to determine the intrinsic mobility.

Note 3 to entry: The drift mobility for electrons and holes can be very different, depending on the residual doping and scattering mechanisms for the given sample.

[SOURCE: IEC 60500-521:2002, 521-02-58, modified – The entry has been adapted to this document.]

3.6 Terms related to the measurement method

3.6.1
four-point probe method
4PP
method to measure electrical sheet resistance of thin films that uses separate pairs of current-carrying and voltage-sensing electrodes

Note 1 to entry: The method is local with a characteristic length scale defined by the probe distance, and generally requires the resistivity variations to be on a much larger scale than the probe spacing. Depending on the positions of the sample-probe contact of the four probe contacts with the surface, different geometrical factors need to be used to extract the sheet resistance.

[SOURCE: ISO/TS 80004-13:2017, 3.3.3.1, modified – The entry has been adapted to this document.]

3.6.2
in-line four-point probe method
type of four-point probe measurement where four-point electrodes are aligned in a row

Note 1 to entry: In this method, four probes contact the test sample in a linear arrangement. A voltage drop is measured between the two inner probes while a current source supplies current through the outer probes.

Note 2 to entry: The distance between the probes needs to be small compared to the lateral dimensions of the sample so that edge effects on the electric field in the sample can be neglected.

Note 3 to entry: The resistance of the sample can be calculated by Ohm's law. Geometrical factors can be used for corrections if the sample is too small or if the measurement is performed close to the edges of the sample.

[SOURCE: IEC TS 62607-6-9:2022, 3.2.3, modified – Note 2 to entry has been deleted.]

3.6.3
van der Pauw method
vdP
type of four probe measurement for samples of arbitrary shape

Note 1 to entry: The van der Pauw method requires four probes placed arbitrarily around the perimeter of the sample, in contrast to the linear four-point probe which is placed on the top of the sample.

Note 2 to entry: The van der Pauw method provides an average sheet resistivity of the sample.

[SOURCE: IEC TS 62607-6-9:2022, 3.2.4, modified – Notes 1 and 4 to entry have been deleted.]