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TECHNICAL SPECIFICATION

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Nanomanufacturing – Key control characteristics –
Part 6-9: Graphene-based material – Sheet resistance: Eddy current method

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CONTENTS

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Part 6-9: Graphene-based material – Sheet resistance: Eddy current method

FOREWORD

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IEC TS 62607-6-9 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
113/569/DTS	113/625/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/standardsdev/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- withdrawn,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

The application of graphene and graphene-related materials as a conductive large-area electrode material has become of rising interest during recent years. Especially in the application of graphene as a replacement material for indium tin oxide (ITO), graphene combines low sheet resistance and high optical transparency. In particular, the application of optically transparent large-area graphene layers has become more important. Hence, the electrical characterization of large-area graphene layers is essential.

However, contacting methods, such as four-probe measurements, can cause damage to the graphene and deteriorate its quality.

Non-contact methods have advantages for measurement of the sheet resistance since damage to the layers is avoided and it is possible to readily scan the film to examine homogeneity.

The sheet resistance can serve as a measure for the electrical characterization due to its direct dependence on conductivity and graphene quality for electrical applications.

NANOMANUFACTURING – KEY CONTROL CHARACTERISTICS –

Part 6-9: Graphene-based material – Sheet resistance: Eddy current method

1 Scope

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

- sheet resistance

for films of graphene-based materials by

- eddy current method.

With this method a coil-generated primary alternating electromagnetic field induces eddy currents in the conducting layer to be measured. The superposition of the primary field with the secondary field induced by the eddy currents is a function of the sheet resistance of the layer.

– The method is applicable for the contactless measurement of the sheet resistance of large area graphene layers on non-conductive substrates. As the method avoids any physical contact, it prevents any mechanical damage to the sensitive graphene layer. Therefore, the method is suitable for electrical characterization and quality control in an industrial fabrication environment.

– Due to the use of two detectors – one above the substrate and one below the substrate – the method is insensitive regarding small deviations from perfect flatness of the substrate.

– The range of graphene layers to be characterized comprises any quality, size and morphology of graphene crystallites. Hence, the applicability of this method spans from high quality, defect-free graphene layers to layers of dried graphene ink.

– The size of the graphene layers to be characterized includes layers larger than 25 mm × 25 mm for single point testing and 50 mm × 50 mm for imaging testing.

– The method can be used for layers of graphene-based material with a sheet resistance in the nominal range of 10 Ω/sq to 5 000 Ω/sq.

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-based material
GBM
graphene material
grouping of carbon-based 2D materials that include one or more of graphene, bilayer graphene, few-layer graphene, graphene nanoplate, and functionalized variations thereof as well as graphene oxide and reduced graphene oxide.

Note 1 to entry: "Graphene material" is a short name for graphene-based material.

3.1.2
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.

3.2 Terms related to the measurement method

3.2.1
eddy current
induced currents circulating along closed paths within a substance

[SOURCE: IEC 60050-121:1998, 121-12-32]

3.2.2
four point probe method
four terminal sensing
method to measure electrical sheet resistance or conductivity of thin films that uses separate pairs of current-carrying and voltage-sensing electrodes

Note 1 to entry: The method is fast, repositionable and local.

Note 2 to entry: There is a comparison of *eddy current* (3.2.1) and four point probe methods in Annex B.

[SOURCE: ISO 80004-13:2017, 5.3.1, modified – Note 2 to entry has been added.]

3.2.3
inline 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 thickness of the layer needs to be small compared to its lateral dimensions so that the sample is approximately two-dimensional.

Note 3 to entry: The distance between the probes shall 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 4 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 in size or if the measurement is performed close to the edges of the sample.

3.2.4
van der Pauw method
type of four probe measurement for samples of arbitrary shape

Note 1 to entry: The thickness of the layer needs to be small compared to its lateral dimensions so that the sample is approximately two-dimensional.

Note 2 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 3 to entry: The van der Pauw method provides an average sheet resistivity of the sample.

Note 4 to entry: The van der Pauw method relies on the assumption that the sample is homogeneous and continuous.

3.2.5
surface conductance measurement using resonant cavity
method to measure the local surface conductance

Note 1 to entry: The measurements are made in an air filled standard R100 rectangular waveguide configuration, at one of the resonant frequency modes, typically at 7 GHz.

Note 2 to entry: Surface conductance measurement by resonant cavity involves monitoring the resonant frequency shift and change in the quality factor before and after insertion of the specimen into the cavity in a quantitative correlation with the specimen surface area.

Note 3 to entry: The thickness of the specimen does not need to be known, but it is assumed that the lateral dimension is uniform over the specimen area. This measurement is suited for atomically thin materials. Only resonant frequency and the area of the specimen are measured. No calibration standards are required. Details are shown in IEC TS 62607-6-4:2016.

Note 4 to entry: Resonance cavity methods and sheet resistance measurement methods do not deliver the same information and therefore do not compete with each other. Resonance cavity methods are mainly used to assess local defects and local properties whereas the sheet resistance measurements describe the electrical performance of a film.

Note 5 to entry: Surface conductance measurement by resonance cavity method is obtained on a very small area only. This technology is applied for the assessment of the individual performance, e.g. of a graphene flake.

Note 6 to entry: The above discussed sheet resistance measurement methods are measuring the ability of a larger area to transport currents through an area requiring the currents to run through various flakes or areas. Here, the number of grain boundaries, their electrical interconnectivity and the individual flake's electrical property matter.

Note 7 to entry: Graphene films can have a good surface conductivity but can be unable to transport currents through an area which is relevant for all applications where graphene is used for its electrical properties.

3.3 Key control characteristics

3.3.1
surface conductance
σ_S
sheet conductance
characteristic physical property of two-dimensional materials describing the ability to conduct electric current

Note 1 to entry: The SI unit of measure of σ_S is siemens (S). In the trade and industrial literature, however, siemens per square (S/sq) is commonly used when referring to surface conductance. "S/sq" is dimensionally equal to "S", but is exclusively used for surface conductance to avoid confusion with electric conductance (G), which shares the same unit of measure: $G = I/U = \sigma_S \cdot (w/l)$.

Note 2 to entry: The surface conductance (σ_S) can be obtained by normalizing conductance G to the specimen width (w) and length (l).

3.3.2
surface resistance
ρ_S
sheet resistance
reciprocal of surface conductance, σ_S

Note 1 to entry: ρ_S is a characteristic property of two-dimensional materials. The SI unit of measure of ρ_S is ohm (Ω). In the trade and industrial literature, however, ohm per square (Ω/sq) is commonly used when referring to surface resistance or sheet resistance.

4 Abbreviated terms

4PP four point probe, test method

EC eddy current, test method

ITO

NIST National Institute of Standards and Technology

PET polyethylene terephthalate

SEMI Semiconductor Equipment and Materials International

VLSI

5 General

5.1 Measurement principle

The eddy current method is a method applied for the characterization of electrical properties such as sheet resistance, conductivity, and local magnetization. Typically, an alternating electromagnetic field (primary field) is inducing eddy currents in the flat, electrically conductive sample of interest. According to Lenz' Law, the induced eddy currents generate a secondary electromagnetic field which is opposed to the primary field. The interaction of the primary field with the secondary field is a function of the sheet resistance of the present conductive layers. This principle is applied to electrically characterize layers without establishing an electrical contact. Generally, there are variants of measurements in physical contact and without physical contact of an electrically isolated eddy current sensor. The non-contacting mode allows the investigation of specimens without any mechanical contact as a potential source of damage or artefacts. The primary field induction and the resulting field measurement can be at different positions. The detecting sensor measures the complex impedance, which picks up the electric power absorption. The sheet resistance is directly correlated with this absorption. The industry is using various probe types and sizes for eddy current testing (see DIN 54140, Section 1-3 - Representation and general characteristics of test coil assemblies).

5.2 Measurement configuration

The measurement is conducted in a transmittance setup, where the sensor parts for field generation and for field measurement are separated by the specimen. The distance between both sensor parts is fixed. The recommended distance is 5 mm to 25 mm. The vertical position of the graphene layer should not vary for more than 10 % of the gap between the upper and lower sensor elements in accordance with the vertical position where the system was calibrated. The gap is fixed and shall not to be changed after system calibration and validation.

This setup supports the measurement on various substrate thicknesses that fit into the measurement gap. The tolerated variation of the thickness within one measurement is 10 % of the gap size. The measurement on different substrate thicknesses and hence different vertical positions in the measurement gap can be achieved by system calibration on these levels. Before each measurement, the user selects a suitable calibration dedicated to the substrate thickness in the tool software.

Reflective measurement setup is not supported by this document since the position tolerance for vertical variation is only given in transmittance mode. This enables robust measurement on all relevant substrates including non-conductive foils. Reflective mode measurements can be done on wafer since those are very flat. In this case, refer to conventional sheet resistance measurement SEMI standards.