IEC TS 62607-6-33

Edition 1.0 2025-10

TECHNICAL SPECIFICATION

Nanomanufacturing - Key control characteristics -
Part 6-33: Graphene-related products - Defect density of graphene: electron energy loss spectroscopy

ICS 07.120

ISBN 978-2-8327-0795-1

IEC TS 62607-6-33:2025-10(en)

THIS PUBLICATION IS COPYRIGHT PROTECTED
Copyright © 2025 IEC, Geneva, Switzerland

All rights reserved. Unless otherwise specified, no part of this publication may be reproduced or utilized in any form or by any means, electronic or mechanical, including photocopying and microfilm, without permission in writing from either IEC or IEC's member National Committee in the country of the requester. If you have any questions about IEC copyright or have an enquiry about obtaining additional rights to this publication, please contact the address below or your local IEC member National Committee for further information.

IEC Secretariat
3, rue de Varembé
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
info@iec.ch
www.iec.ch

About the IEC
The International Electrotechnical Commission (IEC) is the leading global organization that prepares and publishes International Standards for all electrical, electronic and related technologies.

About IEC publications
The technical content of IEC publications is kept under constant review by the IEC. Please make sure that you have the latest edition, a corrigendum or an amendment might have been published.

IEC publications search - webstore.iec.ch/advsearchform
The advanced search enables to find IEC publications by a variety of criteria (reference number, text, technical committee, …). It also gives information on projects, replaced and withdrawn publications.

IEC Just Published - webstore.iec.ch/justpublished
Stay up to date on all new IEC publications. Just Published details all new publications released. Available online and once a month by email.

IEC Customer Service Centre - webstore.iec.ch/csc
If you wish to give us your feedback on this publication or need further assistance, please contact the Customer Service Centre: sales@iec.ch.

IEC Products & Services Portal - products.iec.ch
Discover our powerful search engine and read freely all the publications previews, graphical symbols and the glossary. With a subscription you will always have access to up to date content tailored to your needs.

Electropedia - www.electropedia.org
The world's leading online dictionary on electrotechnology, containing more than 22 500 terminological entries in English and French, with equivalent terms in 25 additional languages. Also known as the International Electrotechnical Vocabulary (IEV) online.

Warning! Make sure that you obtained this publication from an authorized distributor.

CONTENTS

FOREWORD 3
INTRODUCTION 5
1 Scope 6
2 Normative references 6
3 Terms and definitions 6
4 Environmental condition 10
5 Sample 11
5.1 General 11
5.2 Preparation of TEM sample for graphene grown by CVD method 11
5.3 Sample storage 12
6 Measurement principle 12
6.1 General 12
6.2 Data interpretation 13
7 Measurement procedure 14
7.1 General 14
7.2 Detector 14
7.3 Description of the measurement procedure 15
7.3.1 Transmission electron microscope alignment 15
7.3.2 Measurement 15
7.4 Defect density determination 16
7.5 Report of the results 17
Annex A (informative) Format of the test report 18
Annex B (informative) Sampling plan 20
B.1 General 20
B.2 Sampling plan depending on substrate (product type) geometry 20
B.2.1 Circular substrates 20
B.2.2 Square substrates 21
B.2.3 Irregular shaped substrates 22
B.3 Sampling plan depending on TEM grid geometry 23
B.3.1 General 23
B.3.2 300 mesh TEM grid 24
Annex C (informative) Determination of boundary for graphene and defects 25
Annex D (informative) Applications, worked examples: Defect density measurement of graphene grown on Cu substrate by CVD 29
Bibliography 33

Figure 1 – Preparation of TEM sample for graphene grown by CVD method 12
Figure 2 – Electron energy loss spectra of pristine (top) and defective (bottom) graphene 13
Figure 3 – Schematic diagram of defect density measurements by EELS 14
Figure 4 – Schematic diagram of π*/σ* amplitude ratio calculation by spectral image 16
Figure B.1 – Schematic of sample plan for circular substrates (in accordance with IEC TS 62607-6-11:2022) 21
Figure B.2 – Schematic of sample plan for square substrates (in accordance with IEC TS 62607-6-11:2022) 22

Figure B.3 – Example sampling plan for irregular sample (in accordance with IEC TS 62607-6-11:2022) 23
Figure B.4 – Schematic of sample plan for 300 mesh TEM grid 24
Figure C.1 – π*/σ* amplitude map defined as a number or image 27
Figure C.2 – Comparison of spectral backgrounds of graphene, defects, and boundary values (π*/σ* amplitude) in the high-loss energy region 28
Figure D.1 – Preparation of TEM specimens of CVD-grown graphene by direct transfer 29
Figure D.2 – Measurement of defect density of graphene by STEM-EELS 30

Table A.1 – Product identification (in accordance with the relevant blank detail specification) 18
Table A.2 – General material description (in accordance with the relevant blank detail specification) 18
Table A.3 – Measurement related information 19
Table B.1 – Sampling plan for circular substrates (in accordance with IEC TS 62607-6-11:2022) 21
Table B.2 – Sampling plan for square sample (in accordance with IEC TS 62607-6-11:2022) 22
Table B.3 – Sampling plan for 300 mesh TEM grid 24
Table D.1 – Product identification 31
Table D.2 – General material description 31
Table D.3 – Measurement related information 31

INTERNATIONAL ELECTROTECHNICAL COMMISSION

_____

Nanomanufacturing - Key control characteristics - Part 6-33: Graphene-related products - Defect density of graphene: electron energy loss spectroscopy

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.
3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.
6) All users should ensure that they have the latest edition of this publication.
7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
9) IEC draws attention to the possibility that the implementation of this document may involve the use of (a) patent(s). IEC takes no position concerning the evidence, validity or applicability of any claimed patent rights in respect thereof. As of the date of publication of this document, IEC had not received notice of (a) patent(s), which may be required to implement this document. However, implementers are cautioned that this may not represent the latest information, which may be obtained from the patent database available at https://patents.iec.ch. IEC shall not be held responsible for identifying any or all such patent rights.

IEC TS 62607-6-33 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
113/913/DTS	113/932/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, or

– revised.

INTRODUCTION

Quantitative and qualitative measurement of graphene defect is one of the most important factors to determine the quality of graphene. This document presents an analytical method for measuring local defect of graphene or graphene-related materials using scanning transmission electron microscopy (STEM) with electron energy loss spectroscopy (EELS). The scanning capability used in this method enables the defect distribution to be analysed, which can be used in determination of graphene quality. This document will be strengthened and compensated by other methods, such as Raman spectroscopy, X-ray photoelectron spectroscopy (XPS), optical microscopy, etc., which have already been standardized in IEC TC 113.

STEM-based EELS uses electron beams with sub-nanometre scale, which allows structural observations within a highly localized area. Therefore, it is suitable for tracking important defect information that occurs at the atomic scale. Unlike other macroscopic analytical tools (e.g. Raman and XPS), the EELS method sets a clear boundary between graphene and defects that are induced by lattice transformation, doping, and adatoms. Moreover, the method determines the classification and quantity of defects including the number of holes and amorphous regions. These characteristics would complement the existing standards for measuring the defect density in graphene. Particularly, the advancements in STEM-EELS instruments, combined with large-scale data processing technologies, can significantly enhance their complementarity with other macroscopic analysis tools.

The electron energy structure of carbon atoms varies according to the irradiation direction of the electron beam or the sample orientation with respect to electron beam. It can be detected mainly through the change of π* and σ* peaks at the carbon K-edge. This tendency is apparent in the π* peak, which also presents the sp^2 bonding information. Since graphene is a single-layer sp^2 hybrid structure, the intensity ratio between π* and σ* peaks for an ideal graphene is 1:3, which is the same for the π/σ bond ratio. Thus, graphene defects show different electron energy structure compared to pristine graphene. The defect structure of graphene greatly affects the electrical and chemical properties of graphene. Therefore, measuring the defect density of graphene is the key to improving and optimizing its quality for the advancing industrial applications.

1 Scope

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

– defect density (%, nm^2)

of single layer graphene films by

– electron energy loss spectroscopy (EELS in transmission electron microscopy (TEM)).

This document outlines a method for quantitative measurement of defects in graphene at the nanoscale.

The method specified in this document is applicable to single layer graphene acquired via chemical vapour deposition (CVD), roll-to-roll production and exfoliated graphene flakes to estimate the defect density.

In order to obtain reliable data, it is essential that the procedure is consistent for each specified condition from the preparation of the TEM specimen to its observation. It is essential to maintain the spatial resolution below 1 nm by alignment of the beam. The dispersion value, which covers the entire energy loss near edge structure (ELNES) region of the carbon-K edge and maintains the highest energy resolution corresponds to 0,1 eV/ch. Defects in graphene are determined by measuring the spectral differences between sp^2 hybridized and sp^2/sp^3 hybridized atoms, which are obtained by calculating the amplitude ratio of the π* and σ* orbital spectra.

2 Normative references

There are no normative references in this document.