IEC TS 62607-6-6

Edition 1.0 2021-10

TECHNICAL SPECIFICATION

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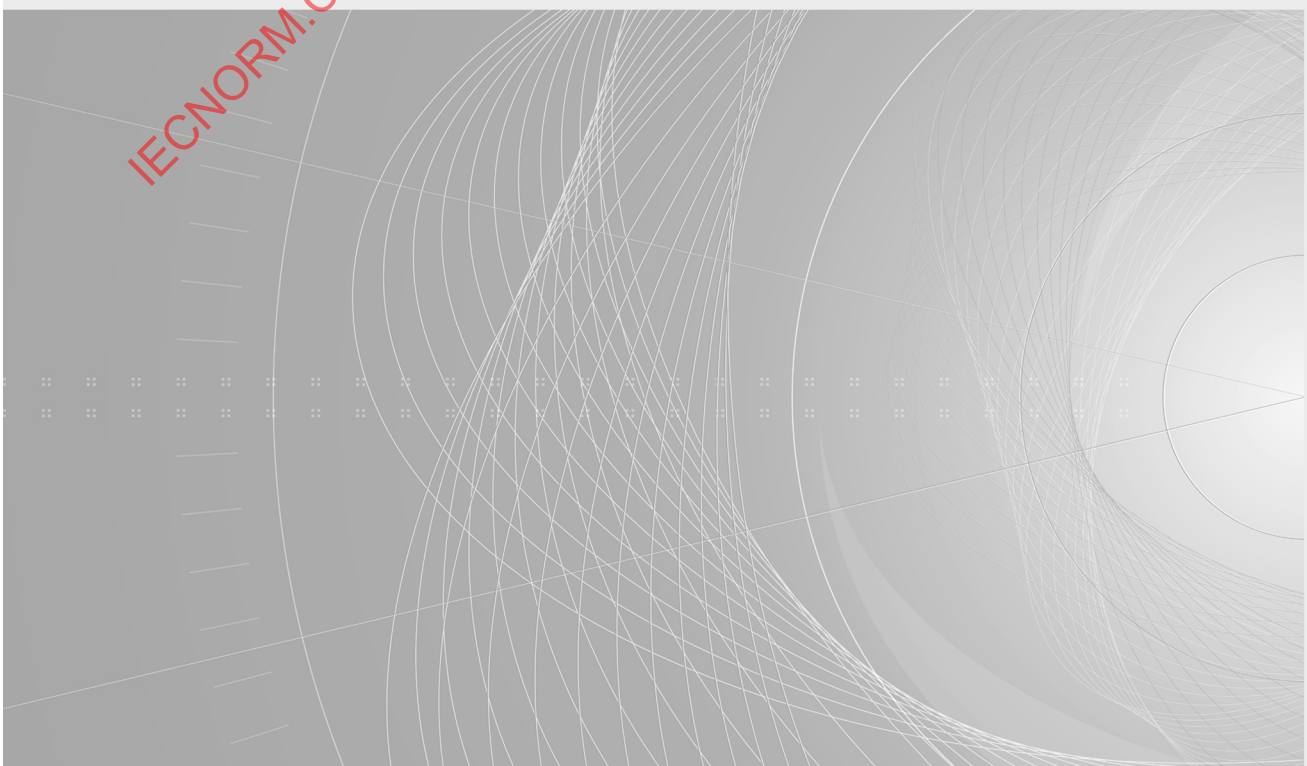
Nanomanufacturing – Key control characteristics – Part 6-6: Graphene – Strain uniformity: Raman spectroscopy



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Nanomanufacturing – Key control characteristics – Part 6-6: Graphene – Strain uniformity: Raman spectroscopy

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CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

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NANOMANUFACTURING – KEY CONTROL CHARACTERISTICS –

Part 6-6: Graphene – Strain uniformity: Raman spectroscopy

FOREWORD

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

Draft	Report on voting
113/579/DTS	113/605/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 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- withdrawn,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, a single layer of carbon atoms arranged in a honeycomb lattice, has a high potential for future nanoelectronic applications thanks to the excellent conductivity and high flexibility of the material. As there is a strong connection between nanoscale lattice deformations and carrier mobility, the uniformity of strain and flatness of the graphene lattice is a key control characteristic for the fabrication of high-quality graphene layers for electronic devices.

One of the most useful methods to evaluate the structural properties of graphene is Raman spectroscopy (see, for example, [1][1]). The method is simple, fast, non-destructive and well understood so that the Raman spectrum can be used as a fingerprint for graphene especially if the sample under evaluation consists of single-layer graphene not too far away from perfection. Things become more complicated if the sample consists of more than one layer, perhaps with different stacking angles and many lattice defects. As this document is intended to support the fabrication of nearly defect-free high-quality single-layer graphene, the interpretation of the Raman spectrum remains relatively simple.

As recently reported [2], nanometre-scale strain variations in graphene give rise to a pseudo-vector disorder potential which allows the pseudo-spin in graphene to flip and thus enables intra-valley backscattering. This scattering mechanism has been identified to be the responsible mechanism for limiting the carrier mobility in high-quality graphene [2]. Interestingly these nanometre-scale strain variations are directly connected to the experimentally observed linewidth of the Raman 2D-peak [3], making this quantity a very interesting measure for estimating the possibility of getting very high mobility graphene devices.

It is important to note that although graphene is a truly two-dimensional material, consisting exclusively of surface atoms, it is embedded in our three-dimensional world. This has the consequence that the properties of graphene are in all cases intrinsically influenced by its intimate surrounding. Thus, substrates or contact gases (in the case of suspended graphene) play a very crucial role when fabricating, transferring and characterizing graphene. Most crucially, substrates, contact gases and moisture are actually becoming part of the graphene system under investigation and there is no way (in practice) of eliminating their influence on the two-dimensional graphene layer.

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

NANOMANUFACTURING – KEY CONTROL CHARACTERISTICS –

Part 6-6: Graphene – Strain uniformity: Raman spectroscopy

1 Scope

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

- strain uniformity

for single-layer graphene by

- Raman spectroscopy.

The width of the 2D-peak in the Raman spectrum is analysed to calculate the strain uniformity parameter which is a figure of merit to quantify the influence of nano-scale strain variations on the electronic properties of the layer. The classification will help manufacturers to classify their material quality to provide an upper limit of the electronic performance of the characterized graphene, to decide whether or not the graphene material quality is potentially suitable for various applications.

- The uniformity of strain measured by this method is applicable for nearly defect free, high-quality single-layer graphene, e.g. synthesized by chemical vapour deposition or graphene integrated into 2D-material heterostructures.
- The method is used if the Raman spectrum shows a visible D-peak with an integrated intensity ratio A(D)/A(G) < 0,1.
- Confocal Raman spectroscopy is used to consistently evaluate the graphene layer according to strain variations on the nanoscale.

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.

IEC TS 62607-6-11, *Nanomanufacturing – Key control characteristics – Part 6-11: Graphene film – Defect density: Raman spectroscopy* [2]

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/

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2 Under preparation. Stage at the time of publication: IEC DTS 62607-6-11.

- 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
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
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.

3.1.4
chemical vapour deposition
CVD
deposition of a solid material by chemical reaction of a gaseous precursor or mixture of precursors, commonly initiated by heat on a substrate

[SOURCE: ISO/TS 80004-13:2017, 3.2.1.1]

3.2 Key control characteristics

3.2.1
strain uniformity
Γ_{80}
quality parameter describing the uniformity of the strain distribution in the graphene layer

Note 1 to entry: Γ_{80} is the 80 % value of the 2D-peak width distribution, $FWHM(2D)_{80}$.

Note 2 to entry: The strain uniformity is a figure of merit describing the quality of graphene layers in respect of the uniformity of strain in the layer. Even if Γ_{80} can be calculated from basic physical principles, this is out of the scope of this document.

Note 3 to entry: The lower the value of Γ_{80}, the higher is the strain uniformity in the graphene layer. Low values of Γ_{80} are a necessary but not sufficient condition for high carrier mobility and high conductivity.

3.3 Measurement related terms

3.3.1
2D-peak
second order Raman peak related to a two-phonon process located at approximately twice the frequency of the D-peak

Note 1 to entry: As well as the D-peak, the 2D-peak is also dispersive with wavelength. The position of the 2D-peak changes strongly with laser energy.

Note 2 to entry: The 2D-peak is always present in the Raman spectrum of graphene and does not need defects to be activated.

3.3.2
D-peak
defect activated Raman peak related to lattice breathing modes in six-carbon rings away from the centre of the Brillouin zone

Note 1 to entry: The D-peak is located between 1 270 cm^{-1} and 1 450 cm^{-1} depending on the wavelength of the excitation laser. The dispersion with wavelength is approximately 50 cm^{-1}/nm.

Note 2 to entry: The D-peak is most intense at defective graphene lattices and disappears for perfect monolayer crystals. Therefore it is often called the disorder band.

3.3.3
D'-peak
defect activated Raman peak in the spectrum of graphene located around 1 620 cm^{-1} originating from scattering away from the Brillouin zone centre

3.3.4
G-peak
Raman peak related to in-plane motion of the carbon atoms located near 1 580 cm^{-1} originating from scattering at the centre of the Brillouin zone

Note 1 to entry: The G-peak can be observed in pristine graphene and does not need lattice defects to occur.

3.3.5
Raman spectroscopy
spectroscopy in which the radiation emitted from a sample illuminated with monochromatic radiation is characterized by an energy loss or gain arising from rotational, vibrational or phonon excitations

[SOURCE: ISO/TS 80004-13:2017, 3.3.1.6]

4 General introduction

4.1 Measurement principle

Raman spectroscopy is a very prominent tool for the investigation of carbon-based material systems [1][4]. In particular, scanning confocal Raman spectroscopy [5] has various beneficial features as a characterization tool for graphene and graphene-related materials such as a particularly high spatial resolution of up to 0,5 µm. If operated with carefully chosen parameters., it is generally a non-destructive method for investigating graphene, Other positive aspects include it being rather fast, and the possibility to analyse graphene that is buried underneath protecting layers of insulating materials, provided they are thin.

In fact, Raman spectroscopy has been shown to be particularly useful for graphene research right from the first isolation of graphene in 2004. The first milestone was made by identifying that the Raman spectrum of single- and bi-layer graphene shows severe differences, so that the technique can be used to distinguish between the exact thickness of graphene and few-layer graphene crystals in their natural crystal stacking order [5][6]. In later years, it was demonstrated that the charge carrier doping of a graphene sample, the amount of mechanical strain in the lattice, as well as nanometre-scaled strain variations [3] and the amount of lattice defects can be determined from a Raman spectrum. All these parameters are essential for the fabrication of graphene-based devices and for the analysis and improvement of synthesis and patterning processes.

It is important to note that strain variations in the graphene lattice are limiting the carrier mobility in "defect-free" graphene samples and allow for an estimate of the achievable carrier mobility in both exfoliated and CVD graphene layers on various substrates.

In a more general sense, the method of scanning confocal Raman mapping can be used to compare graphene layers on different substrates or graphene transfer processes under different fabrication conditions. The experimentally observed linewidth of the 2D-peak is known to contain information about the nanometre-scaled strain variations in graphene [3]. The lower the linewidth, the lower the nanometre-scaled strain variations. This document provides a quantitative method to measure the linewidth including a statistical interpretation to deliver a single value which acts as a key control characteristic of graphene on substrates.

A typical Raman spectrum of defect-free graphene is shown in Figure 1. Raman analysis concentrates on the three most dominating Raman peaks for graphene, the D-, G- and 2D-peaks. Note the absence of the defect-induced D-peak located between 1 270 cm^{-1} and 1 450 cm^{-1}.

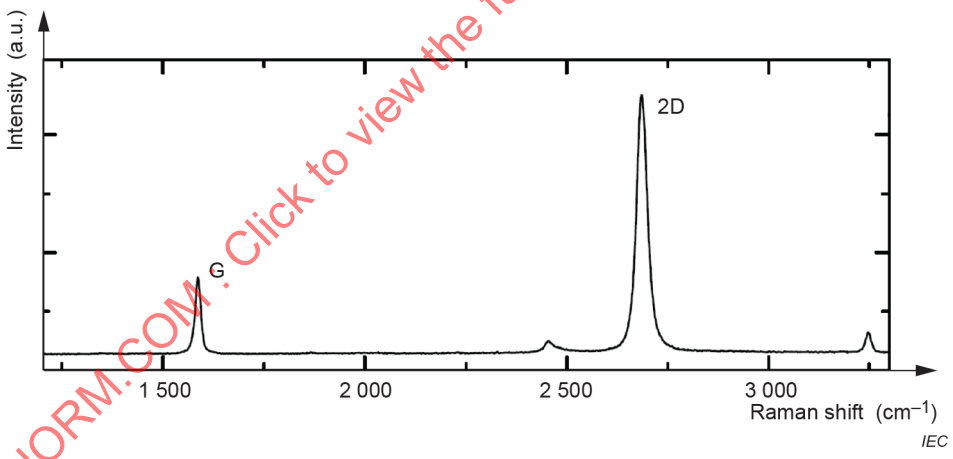


Figure 1 – Typical Raman spectra of an exfoliated graphene flake adopted from [6]

This document addresses pristine or nearly defect-free graphene, similar to that shown in Figure 1. Due to the absence of the D-peak in defect-free samples, it cannot be used to further characterize the quality of the graphene. However, for such defect-free graphene, the 2D-peak, and in particular its linewidth, can be used for the further evaluation of the uniformity of strain which has been proven to be crucial for high carrier mobilities [2][3]. Note that, while strain variations were found to be the dominating limiting factor of the charge carrier mobilities [2], other imperfections can also limit the mobility to a lower value. Therefore, the measured small linewidth is a necessary, but not a sufficient condition to achieve a high mobility value.

4.2 Sample preparation method

Graphene on insulating substrates and certain metals, such as copper, can be reliably characterized by Raman spectroscopy. The sample needs to be sufficiently larger than the

Raman laser spot size. It shall be ensured that the D-, G- and 2D-peaks of the graphene sample are not masked by Raman modes originating from the substrate material.

The sample should be measured as delivered by the supplier. No special sample preparation is required, and no treatment of the sample shall be made as this may change the structural quality and morphology and therefore influence the outcome of the measurement.

As this document addresses purely single-layer graphene, no part of the sample shall contain multi-layers of graphene. For graphene samples with naturally occurring stacking order, this can be directly checked via Raman spectroscopy as only for single-layer graphene does the 2D-peak show a symmetric line shape. If the stacking order differs, e.g. as in twisted bilayer graphene, the assignment of the number of layers via Raman spectroscopy is less straightforward, and complementary techniques such as optical microscopy (optical contrast) or atomic force microscopy shall be used to ensure that the graphene is indeed made of a single layer.

4.3 Test equipment

A state-of-the-art scanning confocal Raman spectroscopy tool with a minimal scan range of 10 µm × 10 µm is required. A laser power lower than 1 mW is recommended for avoiding heating effects (which however may also depend on substrate materials and integration time). An appropriate wavelength (see Table C.1 in Annex C) shall be used for excitation. The obtained spot size (FWHM) in confocal mode should be below 1 µm. This is necessary as the properties of the investigated graphene are averaged over the laser spot. For this document, strain variations on length scales below 0,5 µm are relevant. To ensure a spot size below 1 µm, an appropriate objective (e.g. an achromatic objective with 50× magnification and 0,82 numerical aperture) and pinhole (or optical fibres) should be employed. A spectrometer with a CCD array detector and a suitable grating should be used to fully resolve the 2D-peak and enable a proper fit. The recommended spectral resolution is at least 1,5 cm^{-1}. A typical confocal Raman setup is illustrated in Figure 2.

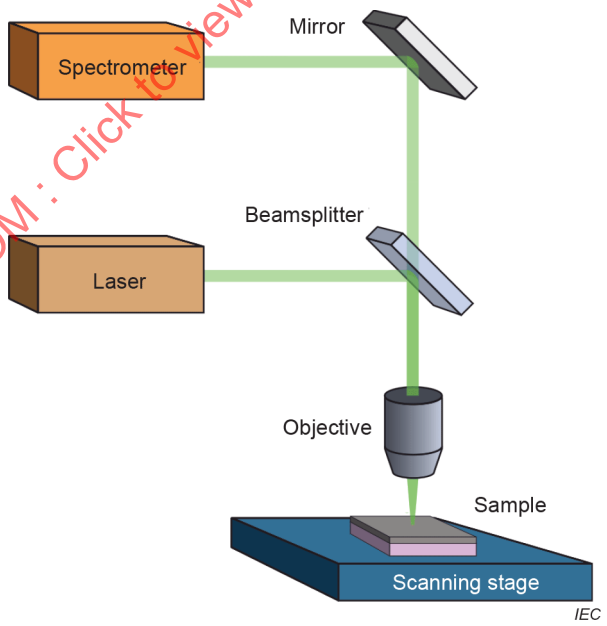


Figure 2 – Schematic illustration of a confocal Raman setup

4.4 Calibration standards

There are no calibration standards required.

5 Measurement procedure

5.1 Calibration of test equipment

The test equipment shall be calibrated according to the requirements of the equipment manufacturer.

5.2 Description of the measurement procedure

Two-dimensional Raman spectroscopy maps shall be recorded in confocal mode, meaning a pin hole is used to eliminate out-of-focus light. The system should allow beam scanning or the sample should be mounted on a movable table with a precision of at least 100 nm.

The maps are taken over a square scan area of 10 µm × 10 µm. Within each scan area 100 spectra (10 × 10) are recorded. The spectral range should be chosen such that the relevant Raman peaks are covered. It is recommended to use a setup where all Raman peaks can be measured in a single acquisition to reduce measurement time. The laser power should not exceed 1 mW on the sample during the measurement to avoid laser induced heating. Examples of Raman spectra of single-layer graphene on different substrates are provided in Annex D.

5.3 Measurement accuracy

To make sure that the 2D linewidth can be extracted, the integration time for each individual spectrum should be adjusted to exceed a signal-to-noise ratio of 20 for the G and 2D lines.

6 Data analysis/interpretation of results

For further analysis no Raman or photoluminescence features originating from the substrate material mask or disturb the D-, G-, and 2D-peaks. After scanning the graphene sample and recording a full Raman spectrum for each spot, the acquired data is further processed by standard peak fitting techniques.

For further analysis, single Lorentzians, defined as

$$f(\omega) = \frac{\frac{1}{\pi} A \frac{1}{2}\Gamma}{(\omega - \omega_0)^2 + \left(\frac{1}{2}\Gamma\right)^2} + f_0$$

where

Γ is the full width at half maximum (FWHM),

A is the integrated intensity of the Lorentzian,

f_0 is the offset, and

ω_0 is the peak position of the Lorentzian,

are fitted to the G- and 2D-peaks and, if possible, to the D-peak. It needs to be made sure that the obtained fits describe the Raman lines appropriately. From the fits, the peak position, integrated intensity and FWHM are extracted for every spectrum.

The area ratio, also called the integrated intensity ratio, A(D)/A(G), which can be obtained from the single Lorentzian fits, is often used as a measure of the defect density within the graphene lattice. For nearly defect-free graphene, which is the subject of this document, the D-peak should not be visible. Nevertheless, the maximum value and mean of all spectra of A(D)/A(G) shall be reported in the test report for information.

As next step, FWHM(2D) is plotted as a two-dimensional map (see Figure 3).

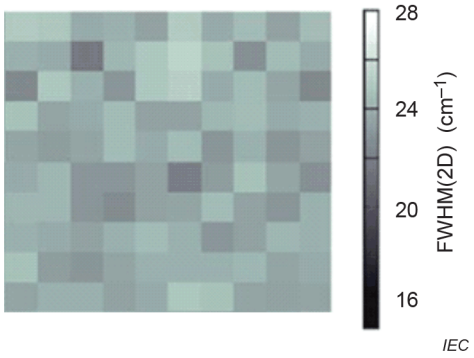
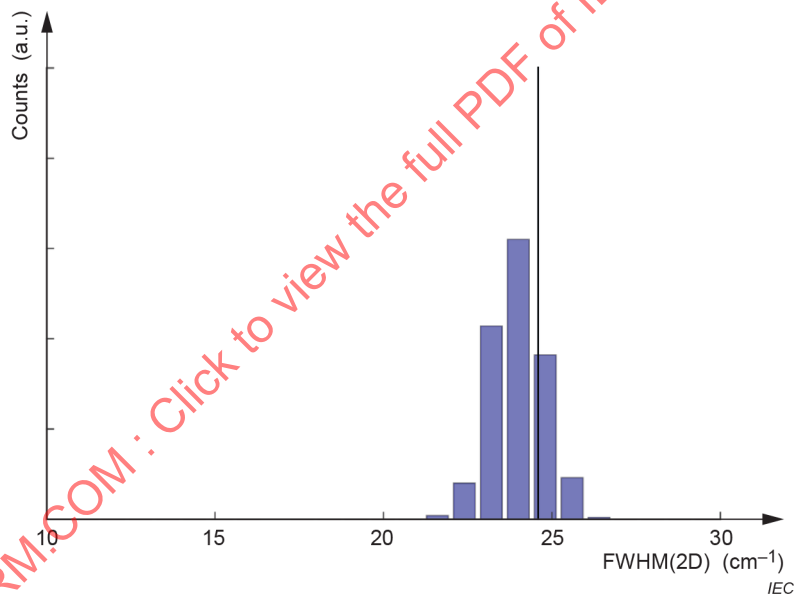


Figure 3 – Example FWHM(2D) Raman map

NOTE This example shows a 10 µm × 10 µm map of FWHM(2D) with 100 sampling points for a graphene sheet encapsulated in hexagonal boron nitride. For all spectra, the 2D-peak is fitted by a single Lorentzian. There is no observable D-peak in this sample.

From this data, one can further perform statistical analysis in terms of a histogram distribution of FWHM(2D). A typical histogram is shown in Figure 4.



The vertical black line indicates the value below which 80 % of the data points are located

Figure 4 – Example FWHM(2D) histogram obtained from the Raman map in Figure 3

The resulting FWHM(2D) distribution is used to evaluate the graphene sample with respect to the strain uniformity by calculating the quantity $FWHM(2D)_{80}$, which measures the threshold below which 80 % of the distribution counts are located (see vertical line in Figure 4).

The resulting threshold quantity $FWHM(2D)_{80}$ allows evaluation of the sample and shall be stated in the test report.

As a general information regarding the strain uniformity, the mean value of the $FWHM(2D)_{80}$ distribution as well as the standard deviation shall be calculated and noted in the test report.

7 Sampling plan

The measurement procedure described in this document probes the spatial variation of the 2D-peak over a standardized square area of 10 µm × 10 µm. It gives no information regarding the uniformity over the whole area of large wafers. To gather information about the distribution of the strain uniformity of the graphene layer over the whole wafer, one of the sampling plans in Annex B shall be used. Depending of the number of measurement points, where each point corresponds to one standardized square area of 10 µm × 10 µm, the measurement time may reach unacceptable measurement time and cost. Therefore, the graphene manufacturer shall develop a strategy to deal with this situation in the qualification process. Which one is chosen may depend on the maturity of the fabrication process, the cost related to testing or agreements between manufacturer and customer.

8 Test report

The test report shall contain all information required to verify the measurement results and trace back to the details of the fabrication conditions of the tested samples. Guidelines are given in Annex A. The test report shall contain at least the following:

– the identification number of the sample;
– the sampling plan used;
– the spectral resolution of the spectrometer;
– the wavelength and spot size of the laser used;
– the signal-to-noise ratio for the Raman spectra based on the 2D-line;
– a typical measured Raman spectrum;
– the maximum value and mean of all spectra of A(D)/A(G);
– the Raman map of the square scan area or a selected typical map if the sampling plan contains several measurement locations;
– the histogram of FWHM(2D) in the scan area or a selected typical map if the sampling plan contains several measurement locations;
– $FWHM(2D)_{80}$ derived from the histogram or a table of the values if the sampling plan contains several measurement locations;
– the mean value of the $FWHM(2D)_{80}$ distribution as well as the standard deviation.

Annex A
(informative)

Format of the test report

Table A.1, Table A.2, Table A.3, Table A.4 and Table A.5 are guidelines to write the report and can be modified to fulfil the requirements of the involved parties.

Table A.1 – Sample identification

Item No	Item		Information
1.1	Supplier		
1.2	Trade name		
1.3	ID number		
1.4	Traceability requirements	☐ Batch number ☐ Serial number ☐ Others, specify	
		Manufacturing date	
1.5	Specification	Number	
		Revision level (e.g. first draft, final draft)	
		Date of issue	

Table A.2 – General material information

Item No	Item	Information
2.1	Material type	
2.2	Physical form	
2.3	Manufacturing method	
2.4	Composition of dispersion	
2.5	Substrate	
2.6	Shelf life	
2.7	Typical batch size	

Table A.3 – Test related information

Item No	Item	Information
3.1	Sampling plan	☐ Circular, specify C-…. ☐ Square, specify S-…. ☐ others, drawing attached
3.2	Excitation wavelength	
3.3	Laser power	
3.4	Number of spectra/measurement	☐ 10 × 10 ☐ others, specify
3.5	A(D)/A(G)	☐ not visible
3.6	Mean value and standard deviation of FWHM(2D) distribution	
3.7	Raman maps	☐ attached ☐ available on request

Table A.4 – Schematic of sample geometry/structure

Item No		
4.1		
	Figure 1: Top view	Figure 2: Cross section

Table A.5 – Measured key control characteristic

Item No	Item	Value
4.1	strain uniformity	

Annex B
(normative)

Sampling plan

B.1 General

The basic measurement on the square scan area of 10 µm × 10 µm provides only local information on the strain uniformity of a graphene layer. If uniformity information over large wafers is needed, a sampling plan is required to identify the exact location of the individual scan areas. Below, a standardized approach for different types of substrates is given.

Which sampling plan is chosen will depend on the required information and measurement time, which is directly related to cost. During the development of a process, it might be necessary to accept a high amount of effort to optimize the process. Nevertheless, over time and with increasing knowledge regarding the process and increasing maturity of the fabrication, this effort can be reduced. While at the beginning all nine points of sampling plan C-A need to be measured, over time the measurement effort might be reduced and sampling plan C-D chosen. Finally, it might be enough to perform plan C-D on merely a fraction of wafers taken at random. Note that an edge exclusion of 6 mm is recommended, but can be reduced if the fabrication process is homogenous.

B.2 Sampling plan for circular substrates

See Figure B.1 and Table B.1.

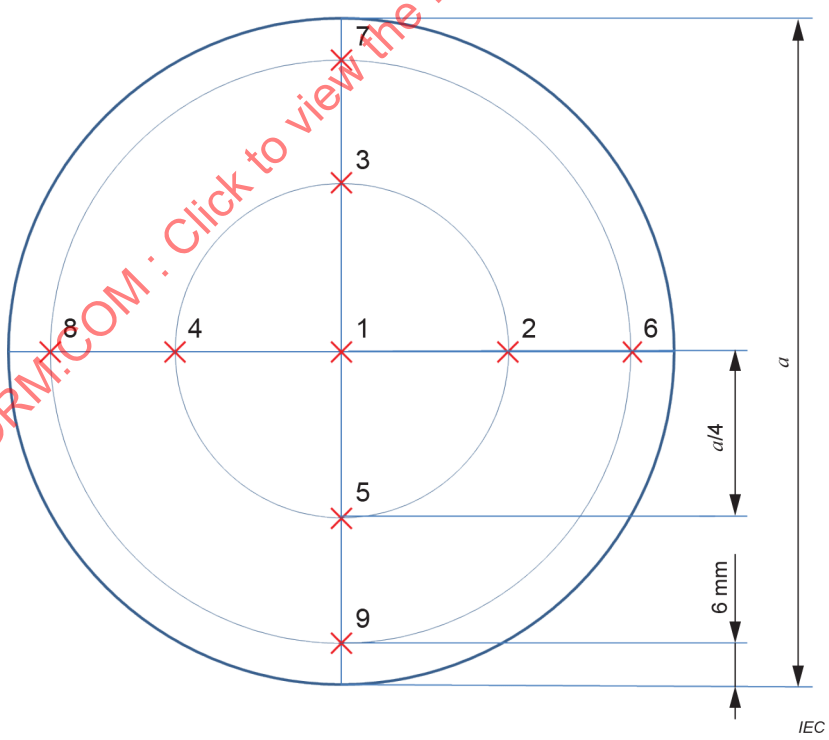


Figure B.1 – Sampling plan for circular substrates of diameter a

Table B.1 – Sampling plan for circular substrates

Sampling plan	Locations								
	1	2	3	4	5	6	7	8	9
C-A	x	x	x	x	x	x	x	x	x
C-B	x	x	x	x	x				
C-C	x					x	x	x	x
C-D	x								

B.3 Sampling plan for square substrates

See Figure B.2 and Table B.2.

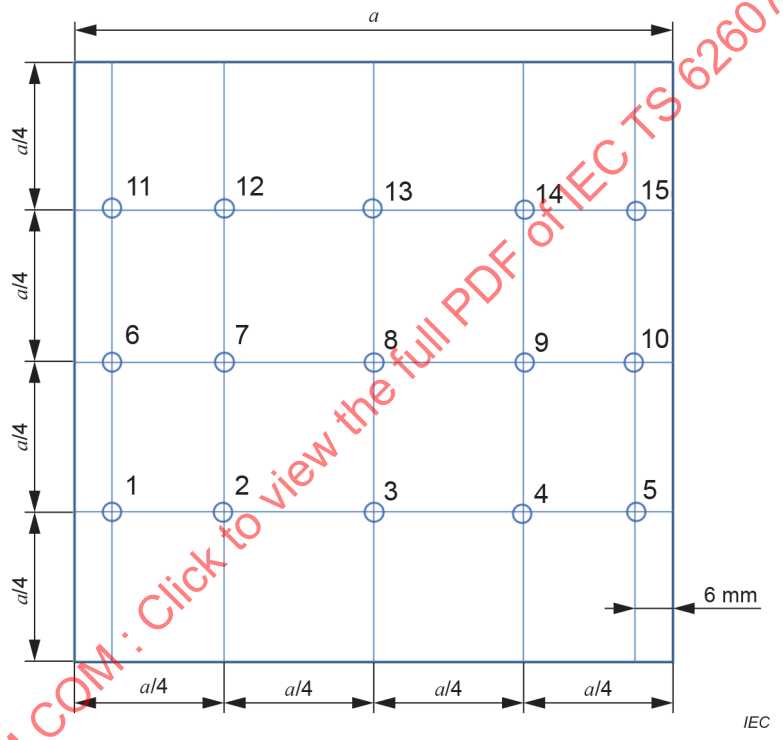


Figure B.2 – Sampling plan for square substrates with edge length a

Table B.2 – Sampling plan for square substrates

Sampling plan	Locations														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
S-A	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
S-B	x	x	x	x	x										
S-C	x		x		x						x		x		x
S-D	x		x		x										
S-E			x												

For the special case of roll-to-roll production (roll width a), the sampling plan for a square substrate can be used accordingly (S-B, S-D or S-E) with the additional information of the distance between repeated measurements along the roll.

B.4 Sampling plan for irregular substrates

For irregularly shaped substrates, a sketch shall be provided showing the locations of the measurement points together with an appropriate scale bar (see Figure B.3).

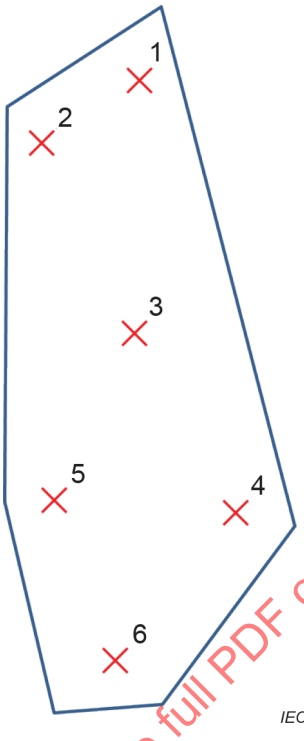


Figure B.3 – Sampling plan for irregular substrates

Annex C
(informative)

Recommendations for wavelengths depending on substrate

The optimal wavelength of the excitation laser strongly depends on the type of substrate. Otherwise, Raman lines originated by the substrate material itself or interferences caused by the layer structure of the sample, e.g. the thickness of the SiO_2-layer of SOS substrates, will affect the measurements. The described method can be well applied to the types of sample configurations given in Table C.1, among others which are not specified in Table C.1.

Table C.1 – Laser wavelength recommendations

Substrate type	Laser wavelength (nm)
SiO_2	514, 532
Hexagonal boron nitride	514, 532
Hafnium oxide	514, 532
Aluminium oxide	514, 532
Copper	457
SiC (0001)	514, 532

Annex D
(informative)

Examples of Raman spectra of single-layer graphene on different substrates

D.1 Example 1: FWHM(2D) = 16,6 cm^{-1} – Graphene encapsulated in hexagonal boron nitride

Figure D.1 shows a Raman spectrum of graphene encapsulated in hexagonal boron nitride (hBN). The 2D peak can be fitted with a single Lorentzian function leading to an extracted FWHM(2D) = 16,6 cm^{-1}. The peak at around 1 365 cm^{-1} stems from the hBN substrate. The red line is a single Lorentzian fit to the 2D line.

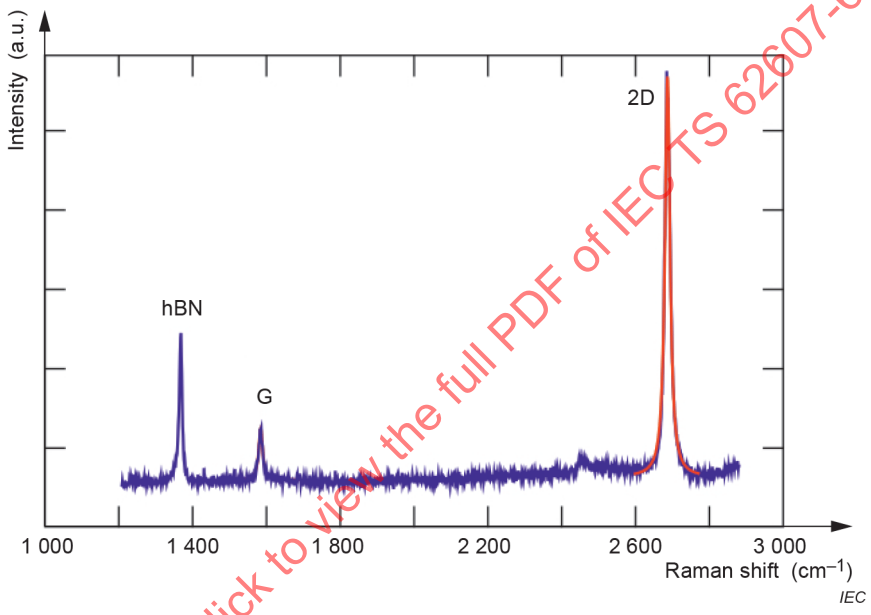


Figure D.1 – Spectrum of graphene encapsulated in hBN

A linewidth of 16,6 cm^{-1} indicates a very small amount of nanometre-scale strain variations in the investigated graphene samples [3]. This is expected for fully hBN encapsulated graphene. Therefore, and as shown in Figure E.1, this structure is suitable for reaching carrier mobilities on the order of 100 000 $cm^2/(Vs)$. Such high mobilities are for example favourable of various terahertz imaging and high-frequency applications as well as highly sensitive Hall sensors.

Nevertheless, note that it is not proof that this high mobility is actually achieved. Other imperfections may limit the mobility to a lower value. Therefore, the measured small linewidth is a necessary, but not a sufficient condition to achieve a high mobility value.

D.2 Example 2: FWHM(2D) = 22,3 cm^{-1} – Graphene on SiO_2 covered with hBN

Figure D.2 shows a Raman spectrum of graphene on SiO_2 covered with hBN. FWHM(2D) is 22,3 cm^{-1}.

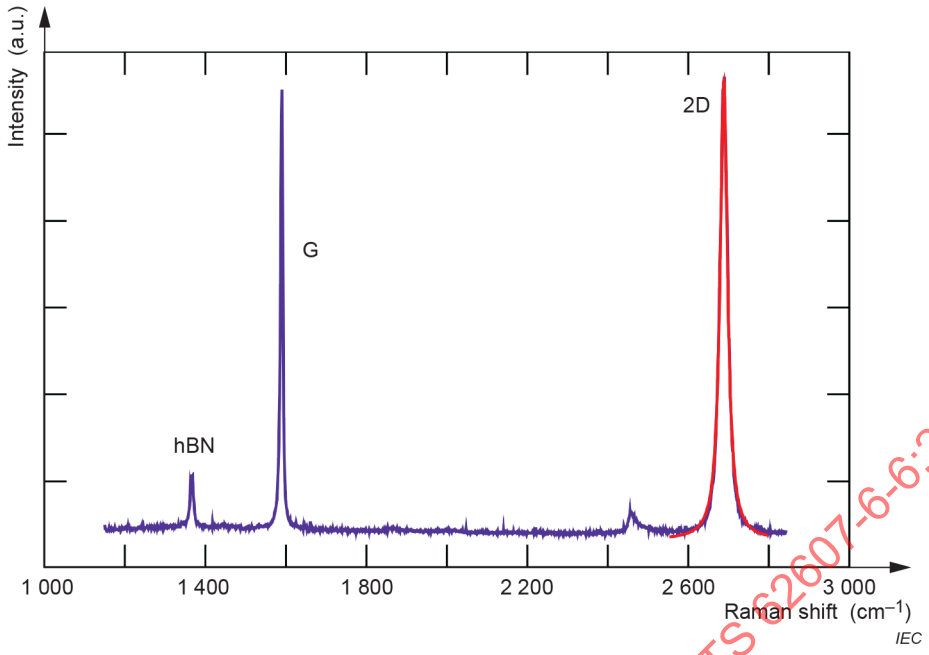


Figure D.2 – Spectrum of graphene on SiO_2 covered with hBN

The application of Figure E.1 suggests that this material is suitable for mobility as high as 2,5 × 10^4 cm^2/(Vs). Importantly, graphene of this quality already fulfils important requirements for various high-frequency and opto-electronic applications

D.3 Example 3: FWHM(2D) = 25,3 cm^{-1} – Graphene on SiO_2

Figure D.3 shows a Raman spectrum of graphene on SiO_2. FWHM(2D) is 25,3 cm^{-1}.

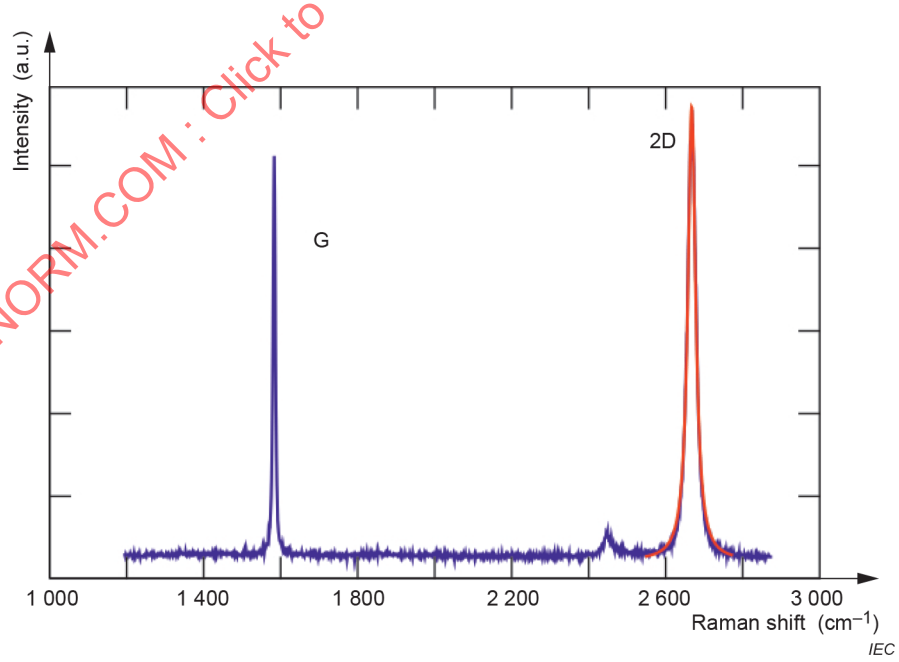


Figure D.3 – Spectrum of graphene on SiO_2

Figure E.1 suggests that this material is capable of showing mobilities as high as 1,1 × 10^4 cm^2/(Vs). Here, the same substrate was used as for the spectrum in Figure D.2.

Showing less than half the mobility, Figure D.3 is an example that the method can be used to optimize fabrication of graphene layers. Applications with less strict requirements on the electronic qualities, such as devices in the field of transparent electrodes and flexible electronics, are in good reach with this type of quality.

D.4 Example 4: FWHM(2D) = 34,8 cm^{-1} – Graphene on SiO_2 substrate covered with hBN

Figure D.4 shows a Raman spectrum of graphene on SiO_2 covered with hexagonal boron nitride. FWHM(2D) is 34,8 cm^{-1}. The peak at around 1 365 cm^{-1} stems from the hBN and is not a graphene D line.

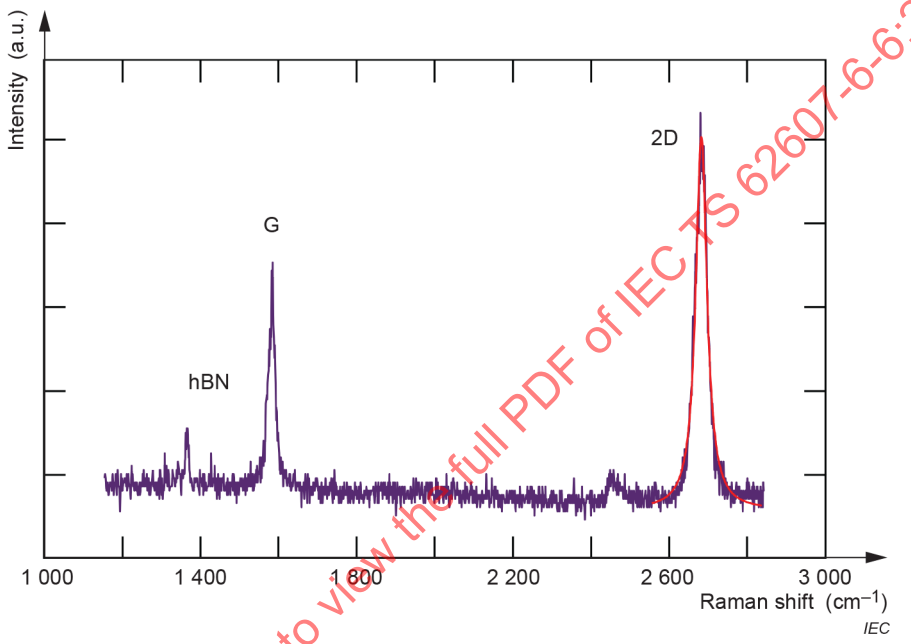


Figure D.4 – Spectrum of graphene on SiO_2 covered with hBN

The application of Figure E.1 suggests that this material is suitable for mobility as high as 3,9 × 10^3 $cm^2/(Vs)$. Various applications on the field of flexible electronics are accessible with this type of graphene performance.

D.5 Example 5: FWHM(2D) = 40,3 cm^{-1} – Graphene on SiO_2 covered with very thin hBN

Figure D.5 shows a Raman spectrum of graphene on SiO_2 covered with a very thin hBN. FWHM(2D) is 40,3 cm^{-1}. The peak at around 1 365 cm^{-1} stems from the hBN and is not a graphene D line. The red line is a single Lorentzian fit to the 2D line.