



BSI Standards Publication

Nanomanufacturing — Key control characteristics

Part 6-10: Graphene-based material — Sheet resistance: Terahertz time-domain spectroscopy

National foreword

This Published Document is the UK implementation of IEC TS 62607-6-10:2021.

The UK participation in its preparation was entrusted to Technical Committee NTI/1, Nanotechnologies.

A list of organizations represented on this committee can be obtained on request to its committee manager.

Contractual and legal considerations

This publication has been prepared in good faith, however no representation, warranty, assurance or undertaking (express or implied) is or will be made, and no responsibility or liability is or will be accepted by BSI in relation to the adequacy, accuracy, completeness or reasonableness of this publication. All and any such responsibility and liability is expressly disclaimed to the full extent permitted by the law.

This publication is provided as is, and is to be used at the recipient's own risk.

The recipient is advised to consider seeking professional guidance with respect to its use of this publication.

This publication is not intended to constitute a contract. Users are responsible for its correct application.

This publication is not to be regarded as a British Standard.

© The British Standards Institution 2023
Published by BSI Standards Limited 2023

ISBN 978 0 539 14153 5

ICS 07.120

Compliance with a Published Document cannot confer immunity from legal obligations.

This Published Document was published under the authority of the Standards Policy and Strategy Committee on 31 March 2023.

Amendments/corrigenda issued since publication

Date	Text affected
------	---------------



IEC TS 62607-6-10

Edition 1.0 2021-10

TECHNICAL SPECIFICATION



**Nanomanufacturing – Key control characteristics –
Part 6-10: Graphene-based material – Sheet resistance: Terahertz time-domain
spectroscopy**

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 07.120

ISBN 978-2-8322-1033-3

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

CONTENTS

FOREWORD.....	4
INTRODUCTION.....	6
1 Scope.....	7
2 Normative references	7
3 Terms and definitions	7
3.1 General terms	7
3.2 Key control characteristics measured according to this document	9
3.3 Terms related to the measurement method described in this document.....	10
4 General	11
4.1 Measurement principle.....	11
4.2 Sample preparation method	13
4.3 Description of measurement equipment	13
4.3.1 Principal components of a THz-TDS system	13
4.3.2 Measurement configurations	14
4.4 Supporting materials	16
4.5 Calibration standards	17
4.6 Measurement conditions	17
5 Measurement procedure	17
5.1 Calibration of the measurement equipment	17
5.2 Detailed protocol of the measurement procedure	17
5.3 Measurement accuracy	19
6 Data analysis / interpretation of results	20
7 Results to be reported	24
7.1 Cover sheet	24
7.2 Measurement conditions	24
7.3 Measurement specific information.....	24
7.4 Measurement results.....	25
Annex A (informative) Worked example	26
A.1 Background.....	26
A.2 Measurement protocol	26
A.3 Test report	29
Annex B (informative) Application examples	33
B.1 General.....	33
B.2 Conductance map of CVD graphene on quartz.....	33
Annex C (informative) Theoretical background.....	35
C.1 Reflection and transmission of plane electromagnetic waves	35
C.2 Transmission coefficient through a thin, conductive film	37
C.3 Sheet conductivity of a thin, conductive film	39
C.3.1 Reflection-mode geometry	40
C.3.2 Transmission-mode geometry.....	41
Annex D (informative) Considerations for custom-built systems	43
D.1 Linearity of the THz-TDS detection system	43
D.2 Calibration of custom-built equipment	43
Bibliography.....	44

Figure 1 – Time trace of a typical THz waveform.....	12
Figure 2 – Sample scheme comprised of a thin film of graphene on a dielectric substrate.	12
Figure 3 – Principal components of a classical THz-TDS system.....	14
Figure 4 – Comparison of different transmission geometries.	15
Figure 5 – Comparison of different reflection geometries	16
Figure 6 – Photograph of a CVD monolayer of graphene on PET substrate.....	21
Figure 7 – THz-TDS conductance and resistance maps of the sample	21
Figure 8 – Analysis of high conductive areas in the conductivity map.....	22
Figure 9 – Analysis of low conductive areas in the conductivity map	22
Figure 10 – Analysis of low resistance areas in the resistance map	23
Figure 11 – Analysis of high resistance areas in the resistance map.....	23
Figure 12 – Conductance maps at two different frequencies: 0,5 THz and 0,75 THz	24
Figure A.1 – Colour map of sheet resistance results at the selected frequency. Sheet resistance map of the wafer at 0.5 THz, with step size 1 mm..	32
Figure B.1 – Photograph of a graphene film on a 100 mm quartz wafer and related conductivity map.....	33
Figure B.2 – Detailed view of subsections.....	34
Figure C.1 – Reflection and transmission for a thin film on a substrate	35
Figure C.2 – Reflection and transmission for a thin film on a substrate.	40
Table A.1 – Illustration of measurement protocol	26
Table A.2 – Product identification	30
Table A.3 – General material description	30
Table A.4 – Sampling plan	31
Table A.5 – Measurement related information	31
Table A.6 – Measurement results: Sheet resistance at the selected frequency.....	32

INTERNATIONAL ELECTROTECHNICAL COMMISSION

NANOMANUFACTURING – KEY CONTROL CHARACTERISTICS –**Part 6-10: Graphene-based material – Sheet resistance:
Terahertz time-domain 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) Attention is drawn to the possibility that some of the elements of this IEC Publication may be the subject of patent rights. IEC shall not be held responsible for identifying any or all such patent rights.

IEC TS 62607-6-10 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
113/568/DTS	113/604/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.

IMPORTANT – The "colour inside" logo on the cover page of this document indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

Graphene is an important nanomaterial in R&D and industry due to its outstanding electrical properties. It is already present in multiple commercial products, and furthermore, it is a strong candidate as an electrical material in numerous new application areas. However, no established method to characterize its local electrical performance and quality across large areas exists yet. The four-point probe method, either as single point or mapping (scanning) technique, is an industry standard for silicon wafers and conventional thin films, but unavoidably leads to damage, due to the physical contact between the tip and the one atom thin graphene film. The microwave resonant cavity method has been demonstrated as a mapping technique for graphene, but with spatial and sample resolution limited by the cavity size: no attempt has been made to scale this technique to industrially relevant sample sizes. Other methods for providing spatial information relating in some way to electrical quality include optical, Raman and scanning electron microscopies. These ones give local information that only indirectly relates to the electrical properties of interest.

The focus of this document is to provide a method to characterize the electrical performance, quality and uniformity of large-area graphene films with terahertz time-domain spectroscopy (THz-TDS). THz-TDS allows for large-area mapping of graphene films in a non-destructive, fast and robust mode, without contact and with no sample preparation at all. This method has no upper limitations in the size of the graphene film to be analysed. It is applicable for statistical process control, comparison of graphene films produced by different vendors, obtaining information about imperfections on the microscale such as grain boundaries and defects, and uniquely allows process modifications and development to be analysed step by step due to its non-destructive property and ability to access buried conductive layers. THz-TDS has been tested against other methods such as van der Pauw (vdP), electrical resistance tomography and calibrated Kelvin probe force microscopy with good matching of results [1] [2]¹.

THz-TDS method provides direct measurements of the sheet resistance, both in transmission and reflection modes [3]. The spatial resolution is related with the diffraction limited THz beam spot size, reaching about 300 μm at 1 THz, and the maximum surface density of measurements is determined by the minimum step-size of the actuator moving the sensor or the sample.

The default sample in this document is monolayer graphene grown by chemical vapour deposition (CVD) on or transferred to a quartz substrate. Nevertheless, the methodology can be extended to graphene on silicon carbide (epitaxial graphene), multilayer graphene, and thin conductors generally, including other 2D materials, on several other dielectric and high resistive substrates including sapphire, silicon coated with silicon dioxide, silicon carbide, polymers and III-V semiconductors, among others. It is noted that for the reflection-mode THz-TDS, the technique tolerates less THz-transparent substrates (e.g. medium to highly doped silicon) than the transmission-mode THz-TDS.

¹ Numbers in square brackets refer to the Bibliography.

NANOMANUFACTURING – KEY CONTROL CHARACTERISTICS –

Part 6-10: Graphene-based material – Sheet resistance: Terahertz time-domain spectroscopy

1 Scope

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

- sheet resistance (R_s)

for films of graphene-based materials by

- terahertz time-domain spectroscopy (THz-TDS).

In this technique, a THz pulse is sent to the graphene-based material. The transmitted or reflected THz waveform is measured in the time domain and transformed to the frequency domain by the fast Fourier transform (FFT). Finally, the spectrum is fitted to the Drude model (or another comparable model) to obtain the sheet resistance.

- This non-contact inspection method is non-destructive, fast and robust for the mapping of large areas of graphene films, with no upper sample size limit.
- The method is applicable for statistical process control, comparison of graphene films produced by different vendors, or to obtain information about imperfections on the microscale such as grain boundaries and defects, etc.
- The method is applicable for graphene grown by chemical vapour deposition (CVD) or other methods on or transferred to dielectric substrates, including but not limited to quartz, silica (SiO_2), silicon (Si), sapphire, silicon carbide (SiC) and polymers.
- The minimum spatial resolution is in the order of 300 μm (at 1 THz) given by the diffraction limited spot size of the THz pulse.

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](http://www.iso.org/obp)

3.1 General terms

3.1.1

graphene

graphene layer

single-layer graphene

monolayer graphene

1LG

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 80004-3:2020, 3.1.13]

3.1.2

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.

3.1.3

thin film

conductive, resistive or dielectric material, usually less than 50 000 Å in thickness, that is deposited onto a substrate by vacuum evaporation, sputtering, or other means

[SOURCE: IEC 60748-23-2:2002, 3.64]

3.1.4

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 may 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]

3.1.5

diffusive conductor

conductor where the dimensions in which electron transport takes place are significantly larger than the mean free path

3.1.6

mean free path

product of the momentum relaxation time and the Fermi velocity

Note 1 to entry: Mean free path can be estimated from the Drude-Boltzmann transport theory:

$$L_{\text{mfp}} = \frac{\mu h}{2e} \sqrt{\frac{N}{\mu}}$$

where h is the Planck's constant, e is the electron charge, μ is the carrier mobility and N is the carrier density.

Note 2 to entry: CVD graphene on SiO₂ has mean free paths in the range 1 nm to 200 nm at room temperature for a doping level of 10¹² cm⁻² (corresponding to carrier mobility being in the $\mu = 100$ cm²/Vs to 20 000 cm²/Vs range) while CVD graphene encapsulated in hexagonal boron nitride can have mean free paths up to 1 µm to 2 µm at room temperature (corresponding to the $\mu = 1 \times 10^6$ cm²/Vs to 2×10^6 cm²/Vs range)

Note 3 to entry: The relationship between sheet conductivity σ_s , carrier density N and carrier mobility μ is given by:

$$\sigma_s = Ne\mu.$$

3.2 Key control characteristics measured according to this document

3.2.1

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.

3.2.2

sheet resistance

R_s

measure of resistance of thin films that are nominally uniform in thickness

Note 1 to entry: Two-dimensional (x-y) sheet resistance (R_s) can be determined for electrically uniform thin films. In rectangular geometry $R_s = R/(L/w)$, where R is the measured resistance, $R = V/I$, L is the distance between parallel electrodes, between which the voltage drop (V) is measured, and w is the length of these electrodes. The electrical current (I) must flow along the plane of the sheet, not perpendicular to it (see Figure 4). The ratio L/w represents the number of squares of the film specimen.

Note 2 to entry: Sheet resistance is expressed in ohms (Ω). However, for the purpose of this procedure, Ω represents the unit ohm/square (Ω/sq).

3.2.3

resistivity

ρ

resistance per unit length of a material of unit cross-sectional area

Note 1 to entry: For a uniform conductor with a uniform cross-section, the relationship between resistivity and

resistance is given by: $R = \rho \frac{l}{A}$

where

A is the cross-sectional area of the conductor;

l is the length of the conductor

The unit of resistivity is the ohm metre ($\Omega \cdot \text{m}$).

Note 2 to entry: For a non-uniform conductor, there is in general no simple relationship between resistivity and resistance.

[SOURCE: ISO 15091:2019, 3.2, modified – Note 1 to entry has been slightly reformulated. Note 2 has been added.]

3.2.4

sheet conductance

G_s

inverse of sheet resistance

$$G_s = 1 / R_s$$

3.2.5

electrical conductivity

σ

reciprocal of the resistivity

Note 1 to entry: Electrical conductivity is given by $\frac{1}{\rho} = \frac{1}{R} \times \frac{l}{A}$. The unit of electrical conductivity is the siemens reciprocal metre ($\text{S} \cdot \text{m}^{-1}$).

Note 2 to entry: The reciprocity is only valid for conductors without directional dependence of the conductivity.

[SOURCE: ISO 15091:2019, 3.4, modified – The symbol γ has been replaced by σ . Note 2 to entry has been added.]

3.2.6

mobility

drift mobility

μ

<of a charge carrier> quantity equal to the ratio 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

[SOURCE: IEC 60050-521:2002, 521-02-58]

3.2.7

charge carrier density

N

density of mobile electrons and/or holes in a material

Note 1 to entry: Expressed in cm^{-3} .

[SOURCE: IEC 62341-1-2:2014, 2.3.1]

3.3 Terms related to the measurement method described in this document

3.3.1

terahertz time-domain spectroscopy

THz-TDS

method to measure the complex-valued dielectric function or conductivity of a material in the terahertz (THz) frequency range (typically 0,1 THz to 5 THz) by the measurement of the temporal shape of an electromagnetic pulse with a duration in the range of picosecond, either reflected from or transmitted through the sample

Note 1 to entry: The amplitude and phase of the frequency components of the signal are compared to those of a reference signal, and can be related to the complex refractive index, permittivity or conductivity of the sample.

3.3.2

signal-to-noise ratio

SNR

ratio of the amplitude of the time trace of the terahertz (THz) electric field signal to the root-mean-square of the noise time trace (measured with the THz beam path blocked)

Note 1 to entry: SNR may be expressed as a level difference in decibels.

Note 2 to entry: SNR can be used to estimate the usable bandwidth of the spectrometer.

3.3.3

dynamic range

DNR

ratio of the amplitude of the frequency trace of the terahertz (THz) electric field signal to the amplitude of the noise frequency trace (measured with the THz beam path blocked)

Note 1 to entry: DNR may be expressed as a level difference in decibels.

Note 2 to entry: DNR can be used to estimate the usable bandwidth of the spectrometer.

3.3.4

spot size

size of the terahertz beam spot on the sample

Note 1 to entry: The terahertz (THz) pulse contains a broad band of frequencies typically ranging from GHz up to several THz depending on the pulse duration. Therefore, the spot size of a THz beam can either be measured at a specific frequency within its bandwidth, or as an average value by a superposition of spot sizes at all frequencies, weighted by their spectral amplitude. The spot size is typically given as FWHM (full width at half maximum) of the spatial field distribution.

Note 2 to entry: The effective THz beam spot is typically measured using the knife-edge method. In this method, a knife-edge is introduced in the area illuminated by the THz beam. The size of the THz spot is measured when the power is half-reduced and it corresponds to the length of the knife-edge introduced.

Note 3 to entry: The effective THz beam spot can be measured with a THz camera.

3.3.5

Rayleigh range

distance from the focal plane of a Gaussian optical beam where the beam radius has increased by a factor of 1,41 (square root of 2)

Note 1 to entry: The Rayleigh range is computed as $Z_R = \pi w_0^2 / \lambda$, where w_0 is the beam radius in the focal plane and λ is the wavelength.

3.3.6

four point probe method

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 fast, repositionable and local, compared to using fixed electrodes.

Note 2 to entry: The method requires the probes making direct contact to the sample, as opposed to four-terminal measurements done via lithographically defined electrodes, i.e. in cloverleaf or Hall bar design.

[SOURCE: ISO/TS 80004-13:2017, 3.3.3.1, modified – In the definition, ", impedance or conductivity" has been deleted. Note 1 has been changed and Note 2 has been added.]

3.3.7

microwave resonant cavity method

method to measure surface conductance or equivalently sheet resistance by resonant cavity that 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 1 to entry: The method is fast and non-contacting.

[SOURCE: ISO/TS 80004-13:2017, 3.3.3.7, modified – The term "non-contact microwave method" is replaced with "microwave resonant cavity method". In the definition, "cavity involves" is replaced with "cavity that involves".]

3.3.8

electrical resistance tomography

method to obtain maps of electrical conductivity of the interior of a two- or three-dimensional sample from a set of four-terminal resistance measurements performed at its boundary

4 General

4.1 Measurement principle

The method to measure the intrinsic resistivity and sheet resistance of a thin conducting film as described in this document is based on terahertz time-domain spectroscopy (THz-TDS). In this technique, an electromagnetic pulse with a typical duration of one picosecond (i.e. the terahertz pulse) is generated and its electric field amplitude and temporal shape is measured in the time domain, as the so-called THz waveform. Figure 1 shows the time trace of a typical THz waveform. The Fourier transform of the time-domain THz waveform provides access to the frequency components of the pulse, which typically spans from 0,1 THz up to 5 THz.

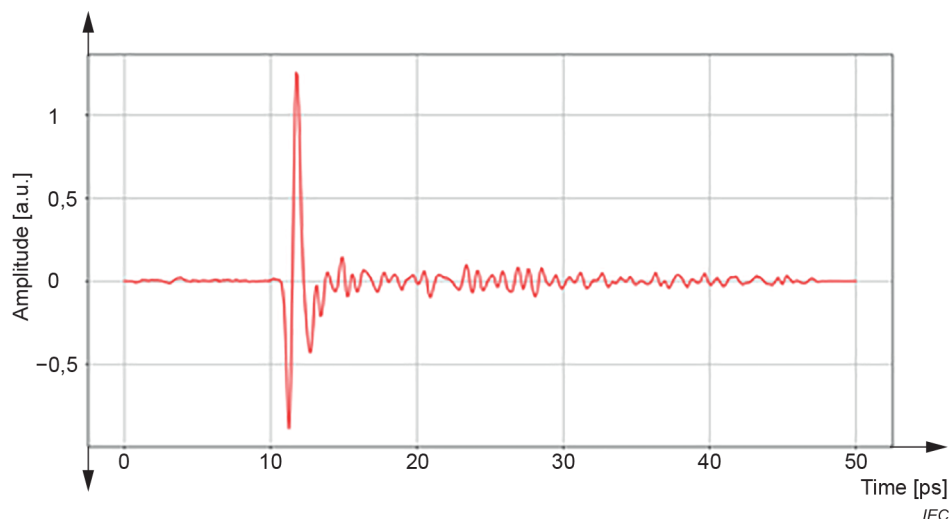


Figure 1 – Time trace of a typical THz waveform

To perform a measurement, the above-mentioned THz pulse is focused on a sample, defined in this document as a thin film of a conducting material (graphene) supported onto a dielectric substrate (see Figure 2). The interaction of the incident THz pulse with the conducting film modifies the amplitude and phase of the transmitted and reflected THz waveforms according to the complex refractive index of the material. The complex refractive index is related to the intrinsic complex resistivity of the material and, in turn, to the sheet resistance. Assuming that the frequency-dependent resistivity is Drude-like [4] or follows another comparable model, the measured resistivity spectrum can be fitted by the given model, and the best-fit values of parameters of the model can be determined.

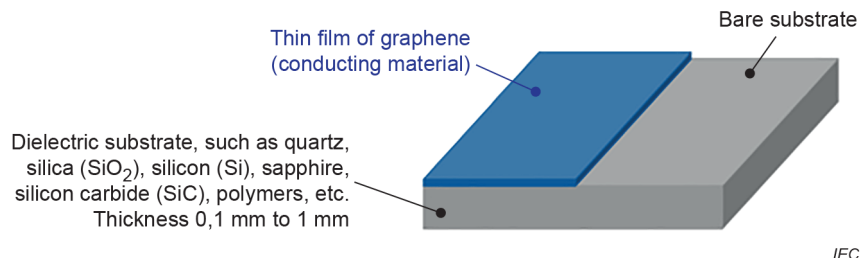


Figure 2 – Sample scheme comprised of a thin film of graphene on a dielectric substrate.

The sheet resistance (R_s) is an extrinsic, generally non-local property of a device and the result of an electrical measurement. The sheet resistivity (ρ_s) is an intrinsic, local property of a material, and is the 2D equivalent of 3D resistivity. For an electrically uniform thin film material, the sheet resistance and sheet resistivity are identical. While for many bulk 3D materials, such as pure metals with uniform conducting properties, a consistent value for the resistivity can be given, this is not generally the case for 2D materials, as these are more vulnerable to environmental conditions, in contact with foreign objects and surfaces, and very frequently contain tears, holes, gaps, cracks and other flaws that leads to a non-uniform current flow. Therefore, the electrical mapping of 2D materials/thin films and following assessment of the uniformity is essential for their correct characterization and THz-TDS provides a suitable method.

THz-TDS technique allows measuring the following electrical parameters:

- sheet resistance (R_s);
- sheet resistivity (ρ_s);
- sheet conductance ($G_s = 1/R_s$);
- sheet conductivity ($\sigma_s = 1/\rho_s$);

- charge carrier mobility (μ);
- charge carrier density (N);
- substrate refractive index (n_{sub}).

It is important to highlight that the sheet resistance, sheet resistivity and charge carrier mobility can be only defined for diffusive conductors, such as graphene and other 2D materials.

Due to the 300 μm spot size (at 1 THz), THz-TDS measures an average of the local sheet conductivity across the spot, or more precisely, the average sheet conductivity weighted by the spot point spread function, or intensity distribution, of the beam spot.

There are two THz-TDS measurement modes: single-point mode and imaging mode.

- Single-point mode refers to a basic THz-TDS measurement where the THz beam is pointed at a relevant position on the sample. The sample signal is compared to a reference measurement to obtain the resistivity at that point with a resolution determined by the spot size.
- Imaging or mapping mode refers to raster scanning the beam over the sample in the focal plane. The signals are recorded as function of the position (x, y) in the sample and compared to one or several reference measurements. The result is a spatial resistivity or conductivity map [1], [2], [5], [6] .

For graphene or other 2D materials, mapping is required to study the distribution of their electrical parameters (ρ_s, σ_s, N, μ) along the surface. The statistical distributions of these parameters are primary descriptors of the sample electrical uniformity and give information about flaws or grain boundaries in the sample. In contrast to electrical measurements, the THz-TDS method is measuring the intrinsic (local) sheet resistivity ρ_s averaged over an area corresponding to the THz spot size, weighted by the Gaussian beam spot intensity. THz-TDS can be performed in two measurement configurations: transmission and reflection, described in detail in 4.3.2.

Further information of the theoretical background and the measurement principle of the sheet resistance and conductance can be found in Annex C.

4.2 Sample preparation method

THz-TDS method requires no sample preparation, nor specific sample handling or storage. It can be advantageous for the measurement accuracy if a part of the sample surface is bare substrate (see Figure 2).

4.3 Description of measurement equipment

4.3.1 Principal components of a THz-TDS system

The principal components of a classical THz-TDS system are listed below and schematized in Figure 3, where the dotted area can be substituted by configurations shown in Figure 4 and Figure 5.

- Femtosecond laser (fs LASER): emits an optical femtosecond pulse.
- Beam splitter (BS): splits the laser output into beams used for THz generation and THz detection.
- Time delay stage: one of the arms of the beam splitter contains an optical delay line for the time scan of the THz transient.
- THz emitter (Tx): generates ultrashort THz pulses when excited by the femtosecond laser, typically in the form of a photoconductive antenna (PCA) or a nonlinear electro-optical crystal (EOX).
- THz detector (Rx): gated by the second part of the laser beam for time-resolved detection of the THz transient, typically another PCA or EOX. The detection signal (photocurrent from the PCA or phase retardation of a probe laser beam through the EOX) is detected by, for example, lock-in techniques and recorded as a function of the position of the optical time delay.