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Nanotechnologies — Vocabulary —

Part 13:
Graphene and related two-dimensional (2D) materials

Nanotechnologies — Vocabulaire —

Partie 13: Graphène et autres matériaux bidimensionnels

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Foreword

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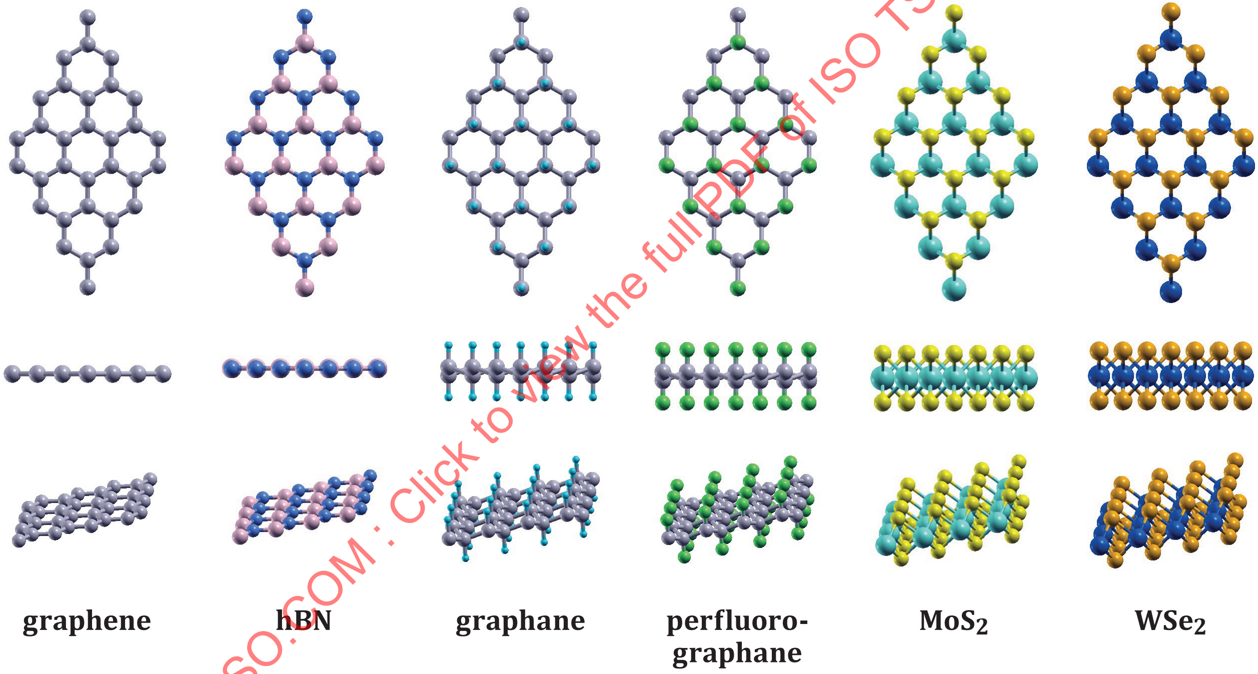
This document was prepared by Technical Committee ISO/TC 229, *Nanotechnologies*, and IEC/TC 113, *Nanotechnology for electrotechnical products and systems*.

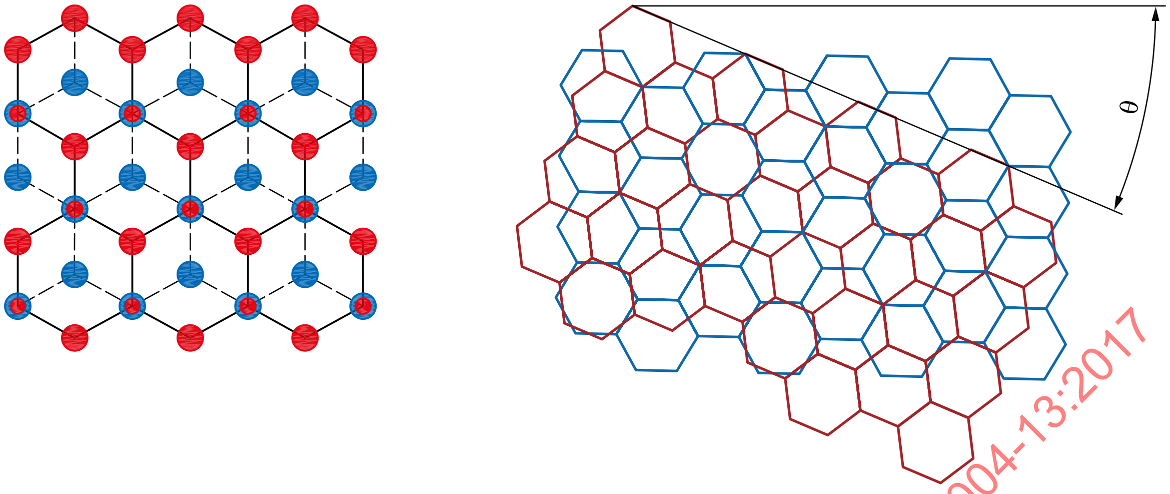
A list of all parts in the ISO 80004 series can be found on the ISO website.

Introduction

Over the last decade, huge interest has arisen in graphene both scientifically and commercially, due to the many exceptional properties associated with this material, properties such as the electrical and thermal conductivity. More recently, other materials with a structure similar to that of graphene have also shown promising properties including monolayer and few-layer versions of hexagonal boron nitride (hBN), molybdenum disulphide (MoS_2), tungsten diselenide (WSe_2), silicene and germanene and layered assemblies of mixtures of these materials. These materials have their thickness constrained within the nanoscale or smaller and consist of between one and several layers. These materials are thus termed two-dimensional (2D) materials as they have one dimension at the nanoscale or smaller, with the other two dimensions generally at scales larger than the nanoscale. A layered material consists of two-dimensional layers weakly stacked or bound to form three-dimensional structures. Examples of 2D materials and the different stacking configurations in graphene are shown in Figure 1. It should be noted that 2D materials are not necessarily topographically flat in reality and can have a buckled structure. They can also form aggregates and agglomerates which can have different morphologies. Two-dimensional materials are an important subset of nanomaterials.



a) Examples of different two-dimensional materials consisting of different elements and structures, as shown by the different coloured orbs and top-down and side views



b) Bernal stacked bilayer graphene (3.1.2.6)

c) turbostratic bilayer or twisted bilayer graphene with relative stacking angle, θ, (3.1.2.7)

ABA trilayer

ABC trilayer

d) Bernal stacked (AB) (3.4.1.10) tri-layer graphene (3.1.2.9) and Rhombohedral (ABC) (3.4.1.11) stacked tri-layer graphene (3.1.2.9)

Figure 1 — Examples of 2D materials and the different stacking configurations in graphene layers

It is important to standardize the terminology for graphene, graphene-derived and related 2D materials at the international level, as the number of publications, patents and organizations is increasing rapidly. Thus, these materials need an associated vocabulary as they become commercialized and sold throughout the world.

This document belongs to a multi-part vocabulary covering the different aspects of nanotechnologies. It builds upon ISO/TS 80004-3, ISO/TS 80004-11 and ISO/TS 80004-6 and uses existing definitions where possible.

Nanotechnologies — Vocabulary —

Part 13:
Graphene and related two-dimensional (2D) materials

1 Scope

This document lists terms and definitions for graphene and related two-dimensional (2D) materials, and includes related terms naming production methods, properties and their characterization.

It is intended to facilitate communication between organizations and individuals in research, industry and other interested parties and those who interact with them.

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 Terms related to materials

3.1.1 General terms related to 2D materials

3.1.1.1
two-dimensional material
2D material
material, consisting of one or several *layers* (3.1.1.5) 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* (3.1.2.1), it is a two-dimensional material up to 10 layers thick for electrical measurements[10],beyond which the electrical properties of the material are not distinct from those for the bulk [also known as *graphite* (3.1.2.2)].

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* (3.1.1.2).

3.1.1.2
nanoplate
nano-object with one external dimension in the nanoscale and the other two external dimensions significantly larger

Note 1 to entry: The larger external dimensions are not necessarily in the nanoscale.

[SOURCE: ISO/TS 80004-2:2015, 4.6]

3.1.1.3
nanofoil
nanosheet
nanoplate (3.1.1.2) with extended lateral dimensions

Note 1 to entry: Nanofoil and nanosheet are used synonymously in specific industrial areas.

Note 2 to entry: Nanofoil and nanosheet extend further with respect to their length and width compared to nanoplate or nanoflake.

[SOURCE: ISO/TS 80004-11:2017, 3.2.1.1]

3.1.1.4
nanoribbon
nanotape
nanoplate (3.1.1.2) with the two larger dimensions significantly different from each other

[SOURCE: ISO/TS 80004-2:2015, 4.10]

3.1.1.5
layer
discrete material restricted in one dimension, within or at the surface of a condensed phase

[SOURCE: ISO/TS 80004-11:2017, 3.1.2]

3.1.1.6
quantum dot
nanoparticle or region which exhibits quantum confinement in all three spatial directions

[SOURCE: ISO/TS 80004-12:2016, 4.1]

3.1.1.7
aggregate
particle comprising strongly bonded or fused particles where the resulting external surface area is significantly smaller than the sum of surface areas of the individual components

Note 1 to entry: The forces holding an aggregate together are strong forces, for example, covalent or ionic bonds or those resulting from sintering or complex physical entanglement or otherwise combined former primary particles.

Note 2 to entry: Aggregates are also termed secondary particles and the original source particles are termed primary particles.

[SOURCE: ISO/TS 80004-2:2015, 3.5, modified – Notes 1 and 2 have been added.]

3.1.2 Terms related to graphene

3.1.2.1
graphene
graphene layer
single-layer graphene
monolayer graphene
single layer of carbon atoms with each atom bound to three neighbours in a honeycomb structure

Note 1 to entry: It is an important building block of many carbon nano-objects.

Note 2 to entry: As graphene is a single layer (3.1.1.5), it is also sometimes called monolayer graphene or single-layer graphene and abbreviated as 1LG to distinguish it from *bilayer graphene* (2LG) (3.1.2.6) and *few-layered graphene* (FLG) (3.1.2.10).

Note 3 to entry: Graphene has edges and can have defects and grain boundaries where the bonding is disrupted.

[SOURCE: ISO/TS 80004-3:2010, 2.11, modified – Notes 2 and 3 have been added.]

3.1.2.2
graphite
allotropic form of the element carbon, consisting of *graphene layers* (3.1.2.1) stacked parallel to each other in a three dimensional, crystalline, long-range order

Note 1 to entry: Adapted from the definition in the IUPAC *Compendium of Chemical Terminology*.

Note 2 to entry: There are two primary allotropic forms with different stacking arrangements: hexagonal and rhombohedral.

[SOURCE: ISO/TS 80004-3:2010, 2.12, modified – Note 2 has been added.]

3.1.2.3
graphane
single layer material consisting of a two-dimensional sheet of carbon and hydrogen with the repeating unit of $(CH)_n$

Note 1 to entry: Graphane is the full hydrogenated form of graphene with carbon bonds in the sp^3 bonding configuration.

3.1.2.4
perfluorographane
single layer material consisting of a two-dimensional sheet of carbon and fluorine with each carbon atom bonded to one fluorine atom with the repeating unit of $(CF)_n$

Note 1 to entry: Perfluorographane has carbon bonds in the sp^3 bonding configuration.

Note 2 to entry: Perfluorographane is sometimes referred to as fluorographene.

3.1.2.5
epitaxial graphene
<graphene> *graphene layer* (3.1.2.1) grown on a silicon carbide substrate

Note 1 to entry: Graphene can be grown by epitaxy on other substrates, for example, Ni(111), but these materials are not termed epitaxial graphene.

Note 2 to entry: This specific definition applies only in the field of graphene. In general, the term “epitaxial” refers to the epitaxial growth of a film on a single crystal substrate.

3.1.2.6
bilayer graphene
2LG
two-dimensional material (3.1.1.1) consisting of two well-defined stacked *graphene layers* (3.1.2.1)

Note 1 to entry: If the stacking registry is known, it can be specified separately, for example, as "Bernal stacked bilayer graphene".

3.1.2.7
twisted bilayer graphene
turbostratic bilayer graphene
tBLG
t2LG
two-dimensional material (3.1.1.1) consisting of two well-defined *graphene layers* (3.1.2.1) that are turbostratically stacked, with a relative *stacking angle* (3.4.1.12), also known as commensurate rotation, rather than *Bernal* (hexagonal) (3.4.1.10) or *rhombohedral stacking* (3.4.1.11),

3.1.2.8
twisted few-layer graphene
t(n+m)LG
two-dimensional material (3.1.1.1) consisting of a few-layers of graphene of n Bernal stacked layers which are situated with a relative *stacking angle* (3.4.1.2) upon m Bernal stacked layers

3.1.2.9
trilayer graphene
3LG
two-dimensional material (3.1.1.1) consisting of three well-defined stacked *graphene layers* (3.1.2.1)

Note 1 to entry: If the stacking registry is known, it can be specified separately, for example, as "twisted trilayer graphene".

3.1.2.10
few-layer graphene
FLG
two-dimensional material (3.1.1.1) consisting of three to ten well-defined stacked *graphene layers* (3.1.2.1)

3.1.2.11
graphene nanoplate
graphene nanoplatelet
GNP
nanoplate (3.1.1.2) consisting of *graphene layers* (3.1.2.1)

Note 1 to entry: GNPs typically have thickness of between 1 nm to 3 nm and lateral dimensions ranging from approximately 100 nm to 100 µm.

3.1.2.12
graphite oxide
chemically modified *graphite* (3.1.2.2) prepared by extensive oxidative modification of the basal planes

Note 1 to entry: The structure and properties of graphite oxide depend on the degree of oxidation and the particular synthesis method.

3.1.2.13
graphene oxide
GO
chemically modified *graphene* (3.1.2.1) prepared by oxidation and exfoliation of *graphite* (3.1.2.2), causing extensive oxidative modification of the basal plane

Note 1 to entry: Graphene oxide is a single-layer material with a high *oxygen content* (3.4.2.7), typically characterized by C/O atomic ratios of approximately 2,0 depending on the method of synthesis.

3.1.2.14

reduced graphene oxide

rGO

reduced *oxygen content* (3.4.2.7) form of *graphene oxide* (3.1.2.13)

Note 1 to entry: This can be produced by chemical, thermal, microwave, photo-chemical, photo-thermal or microbial/bacterial methods or by exfoliating reduced graphite oxide.

Note 2 to entry: If graphene oxide was fully reduced, then graphene would be the product. However, in practice, some oxygen containing functional groups will remain and not all sp^3 bonds will return back to sp^2 configuration. Different reducing agents will lead to different carbon to oxygen ratios and different chemical compositions in reduced graphene oxide.

Note 3 to entry: It can take the form of several morphological variations such as platelets and worm-like structures.

3.1.3 Terms related to other 2D materials

3.1.3.1

2D heterostructure

two-dimensional material (3.1.1.1) consisting of two or more well-defined *layers* (3.1.1.5) of different 2D materials

Note 1 to entry: These can be stacked together in-plane or out-of-plane.

3.1.3.2

2D vertical heterostructure

two-dimensional material (3.1.1.1) consisting of two or more well-defined *layers* (3.1.1.5) of different 2D materials that are stacked out-of-plane

3.1.3.3

2D in-plane heterostructure

two-dimensional material (3.1.1.1) consisting of two or more well-defined *layers* (3.1.1.5) of different 2D materials that are bonded to each other in the in-plane direction

3.2 Terms related to methods for producing 2D materials

3.2.1 Graphene and related 2D material production

3.2.1.1

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 80004-8:2013, 7.2.3]

3.2.1.2

roll-to-roll production

R2R production

<2D material> CVD growth of a *2D material*(s) (3.1.1.1) upon a continuous substrate that is processed as a rolled sheet, including transfer of a 2D material(s) to a separate substrate

3.2.1.3

mechanical exfoliation

<2D material> detachment of separate/individual 2D material *layers* (3.1.1.5) from the body of a material via mechanical methods

Note 1 to entry: There are a number of different methods to achieve this. One method is via peeling, also called the scotch tape method, mechanical cleavage or micromechanical exfoliation/cleavage. Another method is via dry-media ball milling.

3.2.1.4

liquid-phase exfoliation

<2D material> exfoliation of *2D materials* (3.1.1.1) from the bulk layered material in a solvent through hydrodynamic shear-forces

Note 1 to entry: The solvent may be aqueous, organic or ionic liquid.

Note 2 to entry: A surfactant may be used in aqueous dispersions to enable or promote exfoliation and increase stability of the dispersion.

Note 3 to entry: The shear forces may be generated by various methods including ultrasonic cavitation or high-shear mixing.

3.2.1.5

growth on silicon carbide

<graphene> production of *graphene layers* (3.1.2.1) through controlled high temperate heating of a silicon carbide substrate to sublimate the silicon atoms within the substrate, leaving graphene

Note 1 to entry: Graphene may be grown on the carbon-side or silicon-side of the SiC substrate with variations in the resulting number of and stacking of graphene layers.

Note 2 to entry: The product is typically called *epitaxial graphene* (3.1.2.5).

3.2.1.6

graphene precipitation

<graphene> production of *graphene layers* (3.1.2.1) on the surface of a metal through heating and segregation of the carbon present within the metal substrate to the surface

Note 1 to entry: Carbon impurities or dopants within the bulk of the metal may be fortuitous or deliberately introduced.

3.2.1.7

chemical synthesis

<graphene> bottom-up graphene production route using small organic molecules that become linked into carbon rings through surface-mediated reactions and elevated temperatures

3.2.1.8

alcohol precursor growth

<graphene> growth of graphene by introducing an alcohol precursor into a high temperature environment to decompose the alcohol and form graphene

3.2.1.9

molecular beam epitaxy

MBE

process of growing single crystals in which beams of atoms or molecules are deposited on a single-crystal substrate in vacuum, giving rise to crystals whose crystallographic orientation is in registry with that of the substrate

Note 1 to entry: The beam is defined by allowing the vapour to escape from the evaporation zone to a high vacuum zone through a small orifice.

Note 2 to entry: Structures with nanoscale features can be grown in this method by exploiting strain, e.g. InAs dots on GaAs substrate.

[SOURCE: ISO/TS 80004-8:2013, 7.2.13]

3.2.1.10

anodic bonding

<graphene> production of *graphene layers* (3.1.2.1) on a substrate using a graphite precursor in flake form, which is bonded to glass using an electrostatic field and then cleaved off

3.2.1.11
laser ablation
erosion of material from the surface of a target using energy from a pulsed laser

Note 1 to entry: Method of producing nanoscale and microscale features on a surface.

[SOURCE: ISO/TS 80004-8:2013, 7.3.15 – modified]

3.2.1.12
photoexfoliation
detachment of (part of) a *layer* (3.1.1.5)of a *2D material* (3.1.1.1) due to irradiation of a laser beam

Note 1 to entry: For *graphene layers* (3.1.2.1), this method does not induce evaporation or sublimation of the carbon atoms as with *laser ablation* (3.2.1.11).

3.2.1.13
exfoliation via chemical intercalation
<2D materials> production of single or few-layers of *2D materials* (3.1.1.1) by insertion of chemical species between the layers of a thicker layered material, followed by immersion in a liquid combined with the application of mechanical or thermal energy

3.2.1.14
electrochemical exfoliation
<graphene> production of graphene using an ionically conductive solution (electrolyte) and a direct current power source to prompt the structural changes and exfoliation of the graphitic precursor used as the electrode in order to form *layers* (3.1.1.5) of *graphene* (3.1.2.1)

Note 1 to entry: This method offers the potential to use environmentally benign chemicals, with elimination of harsh oxidizers/reducers, relatively fast fabrication rates, and high mass production potential at ambient pressure/temperature.

3.2.1.15
graphite oxidation
production of *graphite oxide* (3.1.2.12) from *graphite* (3.1.2.2) in solution using very strong oxidizers

Note 1 to entry: There are a number of different methods used to produce graphite or *graphene oxide* (3.1.2.13); these include methods from Hummers, Brodie, Staudenmaier, Marcano-Tour [modified version of *Hummers' method* (3.2.1.16)].

3.2.1.16
Hummers' method
production of *graphene oxide* (3.1.2.13) from *graphite* (3.1.2.2) in a sodium nitrate and sulfuric acid solution after the addition of potassium permanganate

Note 1 to entry: This method is described in Reference [11].

3.2.1.17
thermal exfoliation of graphite oxide
production of *reduced graphene oxide* (3.1.2.14) after the introduction of oxygen-containing functional groups between the *graphene layers* (3.1.2.1) in *graphite* (3.1.2.2) and heating, decomposing the introduced species and generation of gases, thus exfoliating the resulting reduced graphene oxide layers

Note 1 to entry: Thermal exfoliation and reduction of *graphite oxide* (3.1.2.12) occur at the same time.

3.2.1.18
gas phase synthesis
<graphene> production of graphene sheets onto a substrate by introducing a carbon precursor into a high temperature gas environment

3.2.1.19
atomic layer deposition
ALD
process of fabricating uniform conformal films through the cyclic deposition of material through self-terminating surface reactions that enable thickness control at the atomic scale

Note 1 to entry: This process often involves the use of at least two sequential reactions to complete a cycle that can be repeated several times to establish a desired thickness.

[SOURCE: ISO/TS 80004-8:2013, 7.2.2]

3.2.2 Nanoribbon production

3.2.2.1
carbon nanotube unzipping
method to produce a graphene *nanoribbon* (3.1.1.4) by splitting a carbon nanotube along its long axis

3.2.2.2
templated growth on SiC
method to produce a graphene *nanoribbon* (3.1.1.4) using a long narrow mask and subsequent *growth on silicon carbide* (3.2.1.5)

3.2.2.3
templated CVD growth
method to produce a graphene *nanoribbon* (3.1.1.4) using a long narrow mask and *CVD* (3.2.1.1)

3.2.2.4
bottom-up precursor growth
method to produce a graphene *nanoribbon* (3.1.1.4) using surface-assisted coupling of molecular precursors and subsequent cyclodehydrogenation

3.2.2.5
electron beam lithographic patterning
method to produce a graphene *nanoribbon* (3.1.1.4) through a top-down approach using electron beam lithography followed by etching to produce the nanoribbon from a *graphene layer* (3.1.2.1)

3.2.2.6
ion beam lithographic patterning
method to produce a graphene *nanoribbon* (3.1.1.4) through a top-down approach using a controlled ion beam to etch the nanoribbon from a *graphene layer* (3.1.2.1)

3.3 Terms related to methods for characterizing 2D materials

3.3.1 Structural characterization methods

3.3.1.1
scanning probe microscopy
SPM
method of imaging surfaces by mechanically scanning a probe over the surface under study, in which the concomitant response of a detector is measured

Note 1 to entry: This generic term encompasses many methods including *atomic force microscopy* (AFM) (3.3.1.2), scanning near field optical microscopy (SNOM), scanning ion conductance microscopy (SICM) and *scanning tunnelling microscopy* (STM) (3.3.1.3).

Note 2 to entry: The resolution varies from that of STM, where individual atoms can be resolved, to scanning thermal microscopy (SThM) in which the resolution is generally limited to around 1 µm.

[SOURCE: ISO 18115-2:2013, 3.30]

3.3.1.2

atomic force microscopy

AFM

method for imaging surfaces by mechanically scanning their surface contours, in which the deflection of a sharp tip sensing the surface forces, mounted on a compliant cantilever, is monitored

Note 1 to entry: AFM can provide a quantitative height image of both insulating and conducting surfaces.

Note 2 to entry: Some AFM instruments move the sample in the *x*-, *y*- and *z*-directions while keeping the tip position constant and others move the tip while keeping the sample position constant.

Note 3 to entry: AFM can be conducted in vacuum, a liquid, a controlled atmosphere or air. Atomic resolution may be attainable with suitable samples with sharp tips and by using an appropriate imaging mode.

Note 4 to entry: Many types of force can be measured, such as the normal forces or the lateral, friction or shear force. When the latter is measured, the technique is referred to as lateral, frictional or shear force microscopy. This generic term encompasses all of these types of force microscopy.

Note 5 to entry: AFMs can be used to measure surface normal forces at individual points in the pixel array used for imaging.

Note 6 to entry: For typical AFM tips with radii < 100 nm, the normal force should be less than about 0,1 µN, depending on the sample material or irreversible surface deformation and excessive tip wear occurs.

[SOURCE: ISO 18115-2:2013, 3.2]

3.3.1.3

scanning tunnelling microscopy

STM

SPM mode for imaging conductive surfaces by mechanically scanning a sharp, voltage-biased, conducting probe tip over their surface, in which the data of the tunnelling current and the tip-surface separation are used in generating the image

Note 1 to entry: STM can be conducted in vacuum, a liquid or air. Atomic resolution can be achieved with suitable samples and sharp probes and can, with ideal samples, provide localized bonding information around surface atoms.

Note 2 to entry: Images can be formed from the height data at a constant tunnelling current or the tunnelling current at a constant height or other modes at defined relative potentials of the tip and sample.

Note 3 to entry: STM can be used to map the densities of states at surfaces or, in ideal cases, around individual atoms. The surface images can differ significantly, depending on the tip bias, even for the same topography.

[SOURCE: ISO 18115-2:2013, 3.34]

3.3.1.4

scanning electron microscopy

SEM

method that examines and analyses the physical information (such as secondary electron, backscattered electron, absorbed electron and X-ray radiation) obtained by generating electron beams and scanning the surface of the sample in order to determine the structure, composition and topography of the sample

[SOURCE: ISO/TS 80004-6:2013, 3.5.5]

3.3.1.5

transmission electron microscopy

TEM

method that produces magnified images or diffraction patterns of the sample by an electron beam which passes through the sample and interacts with it

[SOURCE: ISO/TS 80004-6:2013, 3.5.6]

3.3.1.6
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 18115-2:2013, 5.128 and 5.129, definitions have been combined and reworded.]

3.3.1.7
photoluminescence spectroscopy
PL spectroscopy

spectroscopy of adsorbed and re-radiated photons

[SOURCE: ISO 80004-6:2013, 4.4]

3.3.1.8
X-ray diffraction
XRD

method to obtain crystallographic information about a sample by observing the diffraction pattern due to an X-ray beam hitting a sample

Note 1 to entry: The method can be used to estimate the size of coherent scattering regions.

[SOURCE: ISO 80004-6:2013, 5.2.1]

3.3.1.9
low energy electron microscopy
LEEM

method that examines surfaces where images and/or diffraction patterns of the surfaces are formed by low-energy elastically backscattered electrons generated by a non-scanning electron beam

Note 1 to entry: The method is typically used for the imaging and analysis of very flat, clean surfaces.

Note 2 to entry: Low energy electrons have energies typically in the range 1 eV to 100 eV.

[SOURCE: ISO 80004-6:2013, 3.5.8]

3.3.1.10
low energy electron diffraction
LEED

method to determine the surface structure of single-crystalline materials by bombardment with a collimated beam of low energy electrons and the observation of the diffracted electrons

Note 1 to entry: The interatomic distances can be determined by measuring the distance between the observed spots in the diffracted electron pattern.

3.3.2 Chemical characterization methods

3.3.2.1
Auger electron spectroscopy
AES

method in which an electron spectrometer is used to measure the energy distribution of Auger electrons emitted from a surface

Note 1 to entry: An electron beam in the energy range 2 keV to 30 keV is often used for excitation of the Auger electrons. Auger electrons can also be excited with X-rays, ions and other sources but the term Auger electron spectroscopy, without additional qualifiers, is usually reserved for electron-beam-induced excitation. Where an X-ray source is used, the Auger electron energies are referenced to the Fermi level but, where an electron beam is used, the reference may either be the Fermi level or the vacuum level. Spectra conventionally may be presented in the direct or differential forms.

[SOURCE: ISO/TS 80004-6:2013, 4.16]

3.3.2.2

X-ray photoelectron spectroscopy

XPS

method in which an electron spectrometer is used to measure the energy distribution of photoelectrons and Auger electrons emitted from a surface irradiated by X-ray photons

Note 1 to entry: X-ray sources in common use are unmonochromated Al Kα and Mg Kα X-rays at 1 486,6 eV and 1 253,6 eV, respectively. Modern instruments also use monochromated Al Kα X-rays. Some instruments make use of various X-ray sources with other anodes or of synchrotron radiation.

[SOURCE: ISO/TS 80004-6:2013, 4.18]

3.3.2.3

electron energy loss spectroscopy

EELS

method in which an electron spectrometer measures the energy spectrum of electrons from a nominally monoenergetic source emitted after inelastic interactions with the sample, often exhibiting peaks due to specific inelastic loss processes

Note 1 to entry: The spectrum obtained using an incident-electron beam of about the same energy as in *Auger electron spectroscopy* (AES) (3.3.2.1) or *X-ray photoelectron spectroscopy* (XPS) (3.3.2.2) peak approximates to the energy loss spectrum associated with that peak.

Note 2 to entry: The electron energy loss spectrum, measured with an incident-electron beam, is a function of the beam energy, the angle of incidence of the beam, the angle of emission and the electronic properties of the sample.

[SOURCE: ISO/TS 80004-6:2013, 4.14]

3.3.2.4

energy-dispersive X-ray spectroscopy

EDS

EDX

X-ray spectrometry in which the energy of individual photons are measured by a parallel detector and used to build up a histogram representing the distribution of X-rays with energy

[SOURCE: ISO/TS 80004-6:2013, 4.21]

3.3.2.5

thermal gravimetry

TG

method in which the change in mass of a sample is measured as a function of temperature while the sample is subjected to a controlled temperature programme

[SOURCE: ISO/TS 80004-6:2013, 5.1.2, modified - The term has been changed from “thermogravimetry” to “thermal gravimetry”.]

3.3.2.6

inductively coupled plasma mass spectrometry

ICP-MS

method in which a high-temperature discharge generated in flowing argon by an alternating magnetic field induced by a radio-frequency (RF) load coil that surrounds the tube carrying the gas is detected using a mass spectrometer

[SOURCE: ISO/TS 80004-6:2013, 4.22]

3.3.3 Electrical characterization methods

3.3.3.1
four-terminal sensing
four point probe method
method to measure electrical sheet resistance, impedance 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.

3.3.3.2
graphene Hall bar setup
<graphene> *graphene layer* (3.1.2.1) with appropriate contacts positioned to measure the Hall effect

3.3.3.3
Kelvin-probe force microscopy
KPFM
dynamic-mode AFM using a conducting probe tip to measure spatial or temporal changes in the relative electric potentials of the tip and the surface

Note 1 to entry: Changes in the relative potentials reflect changes in the surface work function.

[SOURCE: ISO 18115-2:2013, 3.12]

3.3.3.4
ultraviolet photoelectron spectroscopy
UPS
method in which an electron spectrometer is used to measure the energy distribution of photoelectrons emitted from a surface irradiated by ultraviolet photons

Note 1 to entry: Ultraviolet sources in common use include various types of discharges that can generate the resonance lines of various gases (e.g. the He I and He II emission lines at energies of 21,2 eV and 40,8 eV, respectively). For variable energies, synchrotron radiation is used.

[SOURCE: ISO 18115-1:2013, 4.22]

3.3.3.5
angle resolved photoemission spectroscopy
ARPES
UPS method (3.3.3.4) in which the angular distribution of photoelectrons from a surface is used to study the electronic properties of the surface

3.3.3.6
photoelectron emission microscopy
PEEM
method of imaging the energy resolved spatial distribution of the photoemission signal with high spatial (50 nm) and spectroscopic (100 meV) resolution

Note 1 to entry: Similar to ARPES but with high spatial resolution (approximately 50 nm). The spectroscopic resolution is approximately 100 meV.

Note 2 to entry: Laboratory ultraviolet and X-ray sources may be used. For variable energies, synchrotron radiation is used.

3.3.3.7
non-contact microwave method
method to measure surface conductance or equivalently sheet resistance 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 1 to entry: The method is fast and non-contacting.

3.4 Terms related to 2D materials characteristics

3.4.1 Characteristics and terms related to structural and dimensional properties of 2D materials

3.4.1.1
defect
<2D material> local deviation from regularity in the crystal lattice of a *2D material* (3.1.1.1)

3.4.1.2
point defect
<2D material> *defect* (3.4.1.1) that occurs only at or around a single lattice point of a *2D material* (3.1.1.1)

Note 1 to entry: Point defects generally involve at most a few missing, dislocated or different atoms creating a vacancy or vacancies, extra atoms (interstitial defects) or replaced atoms.

3.4.1.3
vacancy defect
<2D material> *defect* (3.4.1.1) due to one or more missing atoms of a 2D material *layer* (3.1.1.5)

3.4.1.4
substitution defect
<2D material> *defect* (3.4.1.1) due to an atom of the repeating lattice being replaced by a different atom in a *2D material* (3.1.1.1)

3.4.1.5
line defect
<2D material> *defect* (3.4.1.1) that occurs along an atomic line causing a dislocation of a row in a *2D material* (3.1.1.1)

3.4.1.6
planar defect
<2D material> *defect* (3.4.1.1) occurring in the stacking sequence of the *layers* (3.1.1.5) of a *2D material* (3.1.1.1)

3.4.1.7
sp^3 bonded adatom defect
<graphene> *defect* (3.4.1.1) due to an additional atom being present out-of-plane of the *graphene layer* (3.1.2.1) resulting in an sp^3 hybridized carbon atom or atoms

3.4.1.8
grain boundary
<2D material> in-plane interface between two or more crystalline domains of a *2D material* (3.1.1.1) where the crystallographic direction of the lattice changes

3.4.1.9
dislocation defect
<2D material> defect due to a deviation of the position of atoms relative to one another from a repeating lattice in a *2D material* (3.1.1.1)

3.4.1.10
Bernal stacking
AB stacking
<2D material> stacking of 2D material *layers* (3.1.1.5) on top of one another in such a way that the neighbouring layers only have half of their atoms positioned equivalently in the out of plane direction with every third layer located in the same position in the out of plane axis

Note 1 to entry: The second layer is horizontally displaced with respect to the first layer by half a lattice constant.

3.4.1.11
rhombohedral stacking
ABC stacking
<2D material> stacking of 2D material *layers* (3.1.1.5) consisting of three repeating layers where the second layer is displaced in plane with respect to the first layer by half a lattice constant, and the third layer is horizontally displaced in the same direction, thus every fourth layer is located in the same position in the vertical axis

Note 1 to entry: The three layer system may repeat. The layers are stacked on top of one another in the vertical axis in such a way that the neighbouring layers only have half of their atoms positioned equivalently.

3.4.1.12
stacking angle
<2D material> angle measured in the horizontal plane between the orientations of two *layers* (3.1.1.5) of a *2D material* (3.1.1.1) that are stacked vertically on top of one another

3.4.1.13
turbostratic stacking
<2D material> stacking of *layers* (3.1.1.5) of *2D materials* (3.1.1.1) that cannot be described as *Bernal* (3.4.1.10) or *rhombohedral stacking* (3.4.1.11), instead having a relative *stacking angle* (3.4.1.12) between the layers and which does not allow to develop atomic plane families other than that parallel to the basal plane, because the stacked layers exhibit a relative and random rotational angle or commensurate rotation between the layers

Note 1 to entry: Correspondingly, the only diffraction peaks with three Miller indices seen in XRD (3.3.1.8) patterns are 001 peaks (002, 004, etc.); the others are 2-indices only (typically 10 and 11).

3.4.1.14
domain size
<2D material> lateral dimensions of a single coherent crystalline region within a *layer* (3.1.1.5) of a *2D material* (3.1.1.1)

Note 1 to entry: The terms grain size and crystallite size are synonymous with the term domain size.

Note 2 to entry: If the domain is approximately circular, then this is typically measured using an equivalent circular diameter or if not via x, y measurements along and perpendicular to the longest side.

Note 3 to entry: If an equivalent circular diameter is used, then the term is similar to the crystallite diameter (L_a) which describes the lateral size of a crystal or crystallite region, for example, as measured by *X-ray diffraction* (3.3.1.8) or *Raman spectroscopy* (3.3.1.6).

3.4.1.15
lateral size
flake size
<2D material> lateral dimensions of a 2D material (3.1.1.1) flake

Note 1 to entry: If the flake is approximately circular then this is typically measured using an equivalent circular diameter or if not via x, y measurements along and perpendicular to the longest side.

3.4.1.16
buffer layer
<2D material> *layer* (3.1.1.5) of material between the substrate and the *2D material* (3.1.1.1) displaying the desired properties

Note 1 to entry: The buffer layer will often possess different properties compared to the substrate and the required *2D material* (3.1.1.1) and is often used to accommodate the difference in the crystallographic structures between them.

3.4.1.17
Stone-Wales defect

<2D material> crystallographic defect that involves the change of connectivity of two π-bonded carbon atoms, leading to their rotation by 90° with respect to the midpoint of their bond, hence four adjacent six-membered carbon rings are changed into two five-membered rings and two seven-membered rings

3.4.2 Characteristics and terms related to chemical properties of 2D materials

3.4.2.1
surface contamination

material, generally unwanted, on the sample surface which either is not characteristic of that sample and any process investigated or has arisen from exposure of the sample to particular environments other than those relevant for the original surface or the process to be studied

Note 1 to entry: Common surface contaminants are hydrocarbons and water. Local reactions with these and the environment can lead to a wide range of oxidation and other products.

[SOURCE: ISO 18115-1:2013, 4.459]

3.4.2.2
transfer residue

<2D material> *surface contamination* (3.4.2.1) that is left after the transfer of a *2D material* (3.1.1.1) from one substrate to another

Note 1 to entry: An example is the unwanted surface contamination that is left due to sacrificial polymer used to transfer graphene grown by *CVD* (3.2.1.1) on a metal catalyst to a different substrate.

3.4.2.3
doping

addition of a quantity of different material to the host material with a view to modifying properties

[SOURCE: IEC 62341-1-2, ed. 2.0 (2014-0trans4), 2.2.10]

3.4.2.4
chemical doping

<2D material> *doping* (3.4.2.3) of a *2D material* (3.1.1.1) via exposure of chemical species different to that of the composition of the 2D material

Note 1 to entry: This either leads to substitution of atoms in the lattice or inorganic or organic molecules physically adsorbed onto the surface.

Note 2 to entry: This is typically done to tailor its electronic properties or chemical reactivity.

3.4.2.5
electrochemical doping

<2D material> *doping* (3.4.2.3) of a *2D material* (3.1.1.1) via exposure of the 2D material to an electrochemical environment

3.4.2.6
substrate induced doping

<2D material> *doping* (3.4.2.3) of a *2D material* (3.1.1.1) due to the presence of a substrate

3.4.2.7
oxygen content

<2D material> amount of total oxygen in the *2D material* (3.1.1.1)

3.4.3 Characteristics and terms related to optical and electrical properties of 2D materials

3.4.3.1
substrate interference effects
<2D material> effect allowing single- to few-layer *2D materials* (3.1.1.1) to be identified on silicon substrates with an oxide layer of certain thicknesses, due to the change in interference colour observed

3.4.3.2
anomalous quantum Hall effect
contribution to the quantized Hall resistivity which depends directly on the magnetization of the material

Note 1 to entry: It is often much larger than the ordinary quantum Hall effect.

3.4.3.3
fractional quantum Hall effect
physical phenomenon in which the Hall conductance is quantized in fractional multiples of e^2/h

Note 1 to entry: The quantity e^2/h is half of the quantum of conductance (conductance quantum) G_0.

4 Abbreviated terms

1L	monolayer/single-layer
1LG	monolayer/single-layer graphene
2D	two-dimensional
2L	bilayer
2LG	bilayer graphene
3L	trilayer
3LG	trilayer graphene
CVD	chemical vapour deposition
FL	few-layer
FLG	few-layer graphene
GNP	graphene nanoplatelet
GO	graphene oxide
hBN	hexagonal boron nitride
rGO	reduced graphene oxide