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Nanotechnologies — Vocabulary —

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

Nanotechnologies — Vocabulaire —

Partie 13: Graphène et autres matériaux bidimensionnels (2D)

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of document should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives or www.iec.ch/members_experts/refdocs).

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This document was prepared jointly by Technical Committee ISO/TC 229, *Nanotechnologies*, and Technical Committee IEC/TC 113, *Nanotechnology for electrotechnical products and systems,* and in collaboration with the European Committee for Standardization (CEN) Technical Committee CEN/TC 352, *Nanotechnologies,* in accordance with the Agreement on technical cooperation between ISO and CEN (Vienna Agreement). The draft was circulated for voting to the national bodies of both ISO and IEC.

This second edition cancels and replaces the first edition (ISO/TS 80004-13:2017) which has been technically revised.

The main changes are as follows:

- addition of the term "graphene-related 2D material (GR2M)";
- expansion of defined terms to include "enhanced", "modified", "enabled" and "based", and derivatives thereof;
- indication that use of some terms are deprecated.

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

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

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, 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:

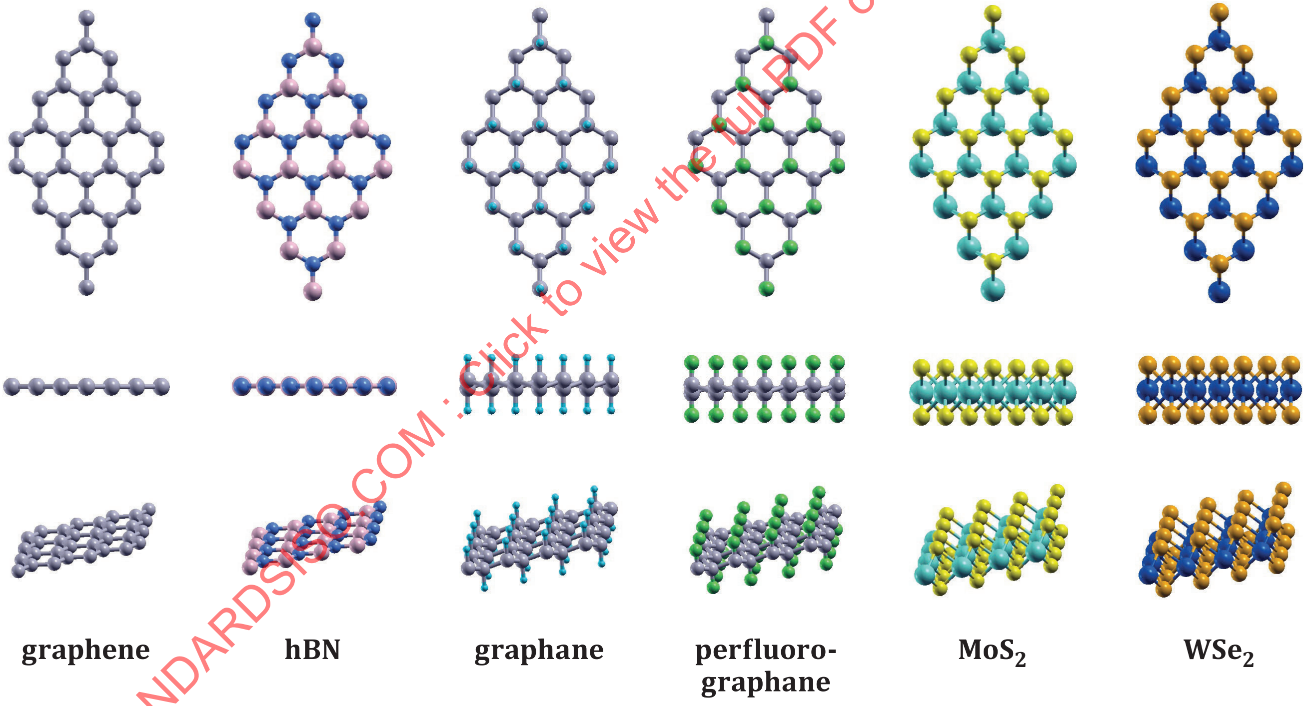
a) monolayer and few-layer versions of hexagonal boron nitride (hBN);

b) transition metal dichalcogenides such as molybdenum disulphide (MoS_2) and tungsten diselenide (WSe_2);

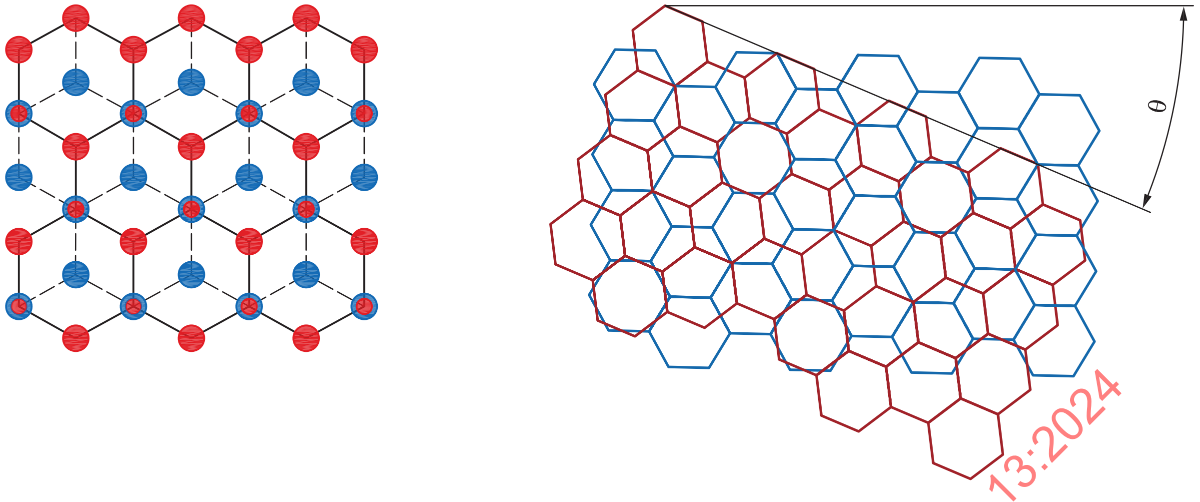
c) silicene and germanene;

d) 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 2D 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. 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. 2D materials are an important subset of nanomaterials.



a) Examples of different 2D 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 (3.1.2.7)

c) Turbostratic bilayer or twisted bilayer graphene with relative stacking angle (θ)(3.1.2.8)

ABA trilayer

ABC trilayer

d) Bernal stacked (AB) (3.4.1.12) tri-layer graphene (3.1.2.10) and rhombohedral (ABC) (3.4.1.13) stacked tri-layer graphene (3.1.2.10)

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

It is important to standardize the terminology for graphene, graphene-related and other 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.

The document contains general terms related to 2D materials, those related to graphene, and those related to other 2D materials. It provides terms related to commonly used methods for producing and characterising 2D materials along, with terms related to 2D materials characteristics. It also includes performance related terms, such as “-enhanced” and “-enabled”, and those related to composition, such as “-based” and “-modified”, as shown in Figure 2.

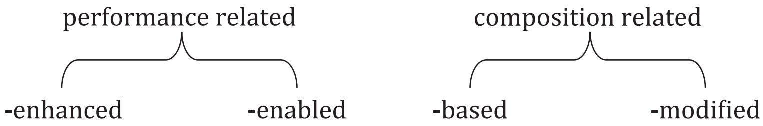


Figure 2 — General terms to describe 2D materials split into performance and composition related terms

This document belongs to a multi-part vocabulary, covering the different aspects of nanotechnologies. It builds upon ISO 80004-1, ISO/TS 80004-3 and ISO/TS 80004-6, and uses existing definitions where possible.

Nanotechnologies — Vocabulary —

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

1 Scope

This document defines terms for graphene, graphene-related two-dimensional (2D) materials and other 2D materials. It includes related terms for production methods, properties and 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

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at http://www.iso.org/obp
- IEC Electropedia: available at http://www.electropedia.org/

3.1 Terms related to materials

3.1.1 General terms related to graphene and other 2D materials

3.1.1.1
two-dimensional material
2D material
material, consisting of one or several *layers* (3.1.1.8) 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 of 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 can contain more than one element.

Note 4 to entry: A two-dimensional material can be a *nanoplate* (3.1.1.5).

3.1.1.2
graphene-related 2D material
GR2M
DEPRECATED: graphene-based material, graphene-material
carbon-based *two-dimensional material* (3.1.1.1) consisting of one to 10 *layers* (3.1.1.8), including *graphene* (3.1.2.1), *graphene oxide* (3.1.2.15), *reduced graphene oxide* (3.1.2.16), and functionalized variations thereof

Note 1 to entry: This includes *bilayer graphene* (3.1.2.7), *trilayer graphene* (3.1.2.10) and *few-layer graphene* (3.1.2.11).

Note 2 to entry: The terms graphene-based material and graphene-material are deprecated here. They have been used to describe materials other than graphene, such as graphene oxide.

Note 3 to entry: "Graphene-related 2D material" is defined in contrast with *graphene-based* (3.1.1.20) and *GR2M-based* (3.1.1.21).

3.1.1.3
flake
<2D material> distinct particle of planar morphology, consisting of 1 or more *layers* (3.1.1.8) of material, with a nanoscale thickness that is significantly smaller than its lateral dimensions

3.1.1.4
sheet
<2D material> *2D material* (3.1.1.1) typically situated upon a substrate, with extended lateral dimensions at the micro to macroscale

3.1.1.5
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 80004-1:2023, 3.3.6]

3.1.1.6
nanofoil
nanosheet
nanoplate (3.1.1.5) 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 80004-1:2023, 3.3.6.2]

3.1.1.7
nanoribbon
nanotape
nanoplate (3.1.1.5) with the two larger dimensions significantly different from each other

[SOURCE: ISO 80004-1:2023, 3.3.10]

3.1.1.8
layer
discrete material restricted in one dimension, within or at the surface of a condensed phase

[SOURCE: ISO 80004-1:2023, 3.6.2]

3.1.1.9

quantum dot

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

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

3.1.1.10

enhanced

<2D material> exhibiting function or performance intensified or improved through the use of a *2D material* (3.1.1.1)

EXAMPLE Graphene oxide-enhanced film.

Note 1 to entry: In enhanced products, the 2D material is typically used in low concentration in the product.

Note 2 to entry: Typical usage is: "X-enhanced Y", where X is the 2D material and Y is the product.

Note 3 to entry: Compare to *based* (3.1.1.19).

3.1.1.11

graphene-enhanced

exhibiting function or performance intensified or improved through the use of *graphene* (3.1.2.1)

EXAMPLE Graphene-enhanced solar cells.

Note 1 to entry: In graphene-enhanced products, the graphene is typically used in low concentration in the product.

Note 2 to entry: In common usage, this term is often incorrectly used to apply to *GR2M* (3.1.1.2) and not just to *single-layer graphene* (3.1.2.1). The correct term is *GR2M-enhanced* (3.1.1.12) or, for example, when referring to graphene nanoplatelets: GNP-enhanced.

Note 3 to entry: Compare to *graphene-based* (3.1.1.20).

3.1.1.12

GR2M-enhanced

DEPRECATED: graphene-enhanced

exhibiting function or performance intensified or improved through the use of *GR2M* (3.1.1.2)

EXAMPLE GR2M-enhanced solar cells.

Note 1 to entry: In GR2M-enhanced products, the GR2M is typically used in low concentration in the product.

Note 2 to entry: Compare to *GR2M-based* (3.1.1.21).

Note 3 to entry: Graphene-enhanced is deprecated since the use of this term only applies to the use of *(single-layer) graphene* (3.1.2.1) as defined by 3.1.1.11.

3.1.1.13

modified

<2D material> intentional addition of the indicated *2D material* (3.1.1.1)

Note 1 to entry: Typical usage is: "X-modified", where X is either a specific 2D material or a class of 2D materials.

Note 2 to entry: The use of this term does not imply property or performance enhancement through the use of the 2D material.

3.1.1.14

graphene-modified

intentional addition of *graphene* (3.1.2.1) to a material

Note 1 to entry: In common usage, this term is often incorrectly used to apply to *GR2M* (3.1.1.2) and not just to *single-layer graphene* (3.1.2.1). The correct term is *GR2M-modified* (3.1.1.15) or, for example, when referring to graphene nanoplatelets: GNP-modified.

Note 2 to entry: The use of this term does not imply property or performance enhancement through the use of graphene.

3.1.1.15
GR2M-modified
DEPRECATED: graphene-modified
intentional addition of *GR2M* (3.1.1.2) to a material

Note 1 to entry: Graphene-modified is deprecated since the use of this term only applies to the use of *single-layer graphene* (3.1.2.1) as defined by 3.1.1.14.

Note 2 to entry: The use of this term does not imply property or performance enhancement through the use of the GR2M.

3.1.1.16
enabled
<2D material> exhibiting function or performance possible through the use of a *2D material* (3.1.1.1)

Note 1 to entry: Typical usage is: "X-enabled", where X is either a specific 2D material or a class of 2D materials.

3.1.1.17
graphene-enabled
exhibiting function or performance possible through the use of *graphene* (3.1.2.1)

Note 1 to entry: This term in common usage is often incorrectly used to apply to *GR2M* (3.1.1.2) and not just to *single-layer graphene* (3.1.2.1). The correct term is *GR2M-enabled* (3.1.1.18) or, for example, when referring to graphene nanoplatelets: GNP-enabled.

3.1.1.18
GR2M-enabled
DEPRECATED: graphene-enabled
exhibiting function or performance possible through the use of *GR2M* (3.1.1.2)

Note 1 to entry: Graphene-enabled is deprecated since the use of graphene-enabled only applies to the use of *single-layer graphene* (3.1.2.1) as defined by 3.1.1.17.

3.1.1.19
based
<2D material> predominately consisting of, or as the key component

EXAMPLE GR2M-based, few-layer graphene-based.

Note 1 to entry: Typical usage is: "X-based Y", where X is either a specific *2D material* (3.1.1.1) or a class of 2D materials and Y is the product.

Note 2 to entry: When using in terms of a product, here the majority of the functional part of the product is composed of the specified 2D material.

3.1.1.20
graphene-based
predominantly consisting of *graphene* (3.1.2.1), or with graphene as a key component

EXAMPLE Graphene-based sensor, graphene-based ink.

Note 1 to entry: Typically, the majority of the functional part of the product is composed of graphene.

Note 2 to entry: While graphene-based is a commonly used expression, in many situations it is more correct to use a different term such as *graphene-enhanced* (3.1.1.11), *graphene-modified* (3.1.1.14) or *graphene-enabled* (3.1.1.17).

Note 3 to entry: In common usage, this term is often incorrectly used to apply to *GR2M* (3.1.1.2) and not just to *single-layer graphene* (3.1.2.1). The correct term is *GR2M-based* (3.1.1.21) or, for example, when referring to graphene nanoplatelets: GNP-based.

3.1.1.21

GR2M-based

DEPRECATED: graphene-based

predominantly consisting of *GR2M* (3.1.1.2), or with GR2M as a key component

Note 1 to entry: Typically, here the majority of the functional part of the product is composed of GR2M.

Note 2 to entry: In many situations, it is more correct to use a different term such as *GR2M-enhanced* (3.1.1.12), *GR2M-modified* (3.1.1.15) or *GR2M-enabled* (3.1.1.18).

Note 3 to entry: Graphene-based is deprecated since the use of graphene-based only applies to the use of *single-layer graphene* (3.1.2.1) as defined by 3.1.1.20.

3.1.2 Terms related to graphene related 2D materials

3.1.2.1

graphene

graphene layer

single-layer graphene

monolayer graphene

1LG

single *layer* (3.1.1.8) 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)* (3.1.2.7) and *few-layered graphene (FLG)* (3.1.2.11).

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

Note 4 to entry: In situations where the word graphene is used as an adjective, including in terms such as graphene-enabled, the term commonly and incorrectly refers to *GR2M* (3.1.1.2) and not just to single-layer graphene.

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.

3.1.2.3

nanographite

flake (3.1.1.3) that consists of *layers* (3.1.1.8) of graphene with a thickness of 11 or more *layers*, with a total thickness of up to 100 nm

3.1.2.4

graphane

single *layer* (3.1.1.8) material consisting of a two-dimensional *sheet* (3.1.1.4) 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 atoms in the sp^3 bonding configuration.

3.1.2.5

perfluorographane

single *layer* (3.1.1.8) material consisting of a two-dimensional *sheet* (3.1.1.4) 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 atoms in the sp^3 bonding configuration.

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

3.1.2.6

epitaxial 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.

3.1.2.7

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”.

3.1.2.8

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* (3.4.1.14), also known as commensurate rotation, rather than *Bernal* (hexagonal) (3.4.1.12) or *rhombohedral stacking* (3.4.1.13)

3.1.2.9

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* (3.1.1.8) which are situated with a relative *stacking angle* (3.4.1.14) upon m Bernal stacked layers

3.1.2.10

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”.

3.1.2.11

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)

3.1.2.12

graphene nanoplatelet

GNP

nanoplate (3.1.1.5) consisting of *graphene layers* (3.1.2.1)

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

3.1.2.13
turbostratic few-layer graphene particle
tFLG particle
minute, non-planar piece of matter with defined physical boundaries consisting of multiple single-layer, bilayer or few-layer graphene stacks at different orientations to each other which can have random and varying stacking angles

Note 1 to entry: These are primary particles and are typically produced through bottom-up production. They contain strong covalent bonds as well as weaker Van der Waals forces.

Note 2 to entry: These can be analysed using TEM. An example is shown in Reference [11].

Note 3 to entry: An example sketch of a tFLG particle is given in Figure 3.

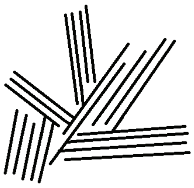


Figure 3 — Example sketch of turbostratic few-layer graphene particle

3.1.2.14
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.

Note 2 to entry: In powder form, restacking of graphite oxide *layers* (3.1.1.8) can occur.

3.1.2.15
graphene oxide
GO
chemically modified *graphene* (3.1.2.1), with 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 O/C atomic ratios of approximately 0,5 (C/O ratios of approximately 2,0) depending on the method of synthesis.

Note 2 to entry: Graphene oxide is predominately prepared by oxidation and exfoliation of graphite.

Note 3 to entry: Oxidative modification can also occur at the edges.

Note 4 to entry: Restacking of graphene oxide can occur. Therefore, care must be taken when preparing samples or products from highly concentrated liquid dispersions as this can lead to agglomeration and aggregation of the primary particles, which are a single-layer.

3.1.2.16
reduced graphene oxide
rGO
reduced *oxygen content* (3.4.2.7) form of *graphene oxide* (3.1.2.15)

Note 1 to entry: This can be produced by chemical, thermal, microwave, photo-chemical, photo-thermal or microbial or 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.

Note 4 to entry: The O/C atomic ratio is approximately 0,1 to 0,5 (C/O ratio 2 to 10).

3.1.2.17
functionalization

process that intentionally alters the surface chemical properties through a distinct chemical process

Note 1 to entry: Functionalized material should be referred to as "functionalized X", where X refers to the material such as graphene, graphene nanoplatelet, etc.

3.1.2.18
functionalized graphene nanoplatelets

functionalized GNPs

graphene nanoplatelets (3.1.2.12) that have had their surface chemical properties intentionally altered through a distinct chemical process

3.1.3 Terms related to other 2D materials

3.1.3.1
MXene

two-dimensional metal carbides and nitrides, with a structure consisting of two or more atomic planes of transition metal (M) atoms packed into a honeycomb-like 2D lattice, that are intervened by either carbon or nitrogen layers (X atoms), or both, occupying the octahedral sites between the adjacent transition metal atomic planes

Note 1 to entry: Oxygen can also be present in the X sites in some MXenes as oxycarbides or oxynitrides.

3.1.3.2
transition metal dichalcogenide

TMDC

TMD

semiconducting *two-dimensional material* (3.1.1.1) consisting of three atomic planes: a central one with transition metal atoms between two planes of chalcogen atoms, in a honeycomb, hexagonal lattice with threefold symmetry

Note 1 to entry: Examples of TMDs include MoS2, WS_2, $MoSe_2$, Wse_2, $MoTe_2$.

3.1.3.3
silicene

two-dimensional material (3.1.1.1) consisting of a single *layer* (3.1.1.8) of silicon atoms with each atom bound to three neighbours in a honeycomb structure

Note 1 to entry: A 2D layer of silicene is not completely flat, but instead has a corrugated morphology.

3.1.3.4
germanene

two-dimensional material (3.1.1.1) consisting of a single *layer* (3.1.1.8) of germanium atoms with each atom bound to three neighbours in a honeycomb structure

Note 1 to entry: A 2D layer of germanene is not completely flat, but instead has a corrugated morphology.

3.1.3.5
stanene

two-dimensional material (3.1.1.1) consisting of a single *layer* (3.1.1.8) of tin atoms with each atom bound to three neighbours in a honeycomb structure

Note 1 to entry: A 2D layer of stanene is not completely flat, but instead has a corrugated morphology.

3.1.3.6
phosphorene

two-dimensional material (3.1.1.1) consisting of a single *layer* (3.1.1.8) of black phosphorus, consisting of phosphorus atoms each bound to three neighbours in a quadrangular pyramid structure via sp^3 hybridisation

3.1.3.7

2D heterostructure

two-dimensional material (3.1.1.1) consisting of two or more well-defined *layers* (3.1.1.8) of different 2D materials

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

3.1.3.8

2D vertical heterostructure

two-dimensional material (3.1.1.1) consisting of two or more well-defined *layers* (3.1.1.8) of different 2D materials that are stacked out-of-plane

Note 1 to entry: This is sometimes referred to as a van der Waals heterostructure.

3.1.3.9

2D in-plane heterostructure

2D lateral heterostructure

two-dimensional material (3.1.1.1) consisting of two or more well-defined *layers* (3.1.1.8) 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

top-down production

<2D material> process to create *two-dimensional materials* (3.1.1.1) from larger objects

Note 1 to entry: These processes typically involve energy in different forms in order to exfoliate the *layers* (3.1.1.8) apart.

Note 2 to entry: For graphene related 2D materials, graphite is the starting material.

3.2.1.2

bottom-up production

<2D material> process to create *two-dimensional materials* (3.1.1.1) from smaller fundamental units

Note 1 to entry: For graphene related 2D materials, many of these processes use carbon-rich gases and high temperatures.

3.2.1.3

chemical vapour deposition

CVD

deposition of a solid material onto a substrate by chemical reaction of a gaseous precursor or mixture of precursors, commonly initiated by heat

[SOURCE: ISO/TS 80004-8:2020, 8.2.4]

3.2.1.4

metal organic chemical vapour deposition

MOCVD

chemical vapour deposition (3.2.1.3) by chemical reaction of a precursor or mixture of precursors, including typically one metalorganic, without the need of a catalyst substrate

Note 1 to entry: The material is typically deposited straight onto a semiconductor substrate.

3.2.1.5

plasma-enhanced chemical vapour deposition

PECVD

chemical vapour deposition (3.2.1.3) with chemical reaction rates enhanced by using plasma

Note 1 to entry: This allows deposition at lower temperatures than conventional CVD.

3.2.1.6
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* (3.1.1.4), often including transfer of a 2D material(s) to a separate substrate

3.2.1.7
mechanical exfoliation

<2D material> detachment of individual *2D material* (3.1.1.1) *layers* (3.1.1.8) from the body of a material via mechanical methods

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

3.2.1.8
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 can be aqueous, organic or ionic liquid.

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

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

3.2.1.9
growth on silicon carbide

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

Note 1 to entry: Graphene can 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* (3.1.2.6).

3.2.1.10
graphene precipitation

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 can be fortuitous or deliberately introduced.

3.2.1.11
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

3.2.1.12
alcohol precursor growth

<graphene> growth of *graphene* (3.1.2.1) by introducing an alcohol precursor into a high temperature environment to decompose the alcohol and form graphene

3.2.1.13
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 80004-8:2020, 8.2.13]

3.2.1.14
anodic bonding

<graphene> production of *graphene layers* (3.1.2.1) on a substrate using a graphite precursor in *flake* (3.1.1.3) form, which is bonded to glass using an electrostatic field and then cleaved off

3.2.1.15
laser ablation

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

Note 1 to entry: Laser ablation is a method of producing nanoscale and microscale features on a surface.

[SOURCE: ISO/TS 80004-8:2020, 8.3.15, modified — Minor rewording.]

3.2.1.16
photoexfoliation

detachment of (part of) a *layer* (3.1.1.8) 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* (3.2.1.15).

3.2.1.17
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

3.2.1.18
electrochemical exfoliation

<graphene> production of *graphene* (3.1.2.1) 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* (3.1.1.8) of graphene

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

3.2.1.19
graphite oxidation

production of *graphite oxide* (3.1.2.14) from *graphite* (3.1.2.2) in a solution using very strong oxidizers

Note 1 to entry: There are a number of different methods used to produce graphite or *graphene oxide* (3.1.2.15); these include methods from Hummers, Brodie, Staudenmaier, and Marcano-Tour [modified version of *Hummers' method* (3.2.1.20)].

3.2.1.20
Hummers' method

production of *graphene oxide* (3.1.2.15) 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 [12].

3.2.1.21
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* (3.1.1.8)

Note 1 to entry: Thermal exfoliation and reduction of *graphite oxide* (3.1.2.14) occur at the same time.

3.2.1.22
gas phase synthesis
<GR2M> production of *GR2M* (3.1.1.2) by introducing a carbon precursor into a high temperature gas environment

3.2.1.23
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 80004-8:2020, 8.2.2]

3.2.1.24
pyrolysis
<GR2M> irreversible chemical decomposition of organic matter to create *GR2M* (3.1.1.2) due to an increase in temperature without oxidation

Note 1 to entry: This process also requires a separation step in order to separate the GR2M from other materials present.

[SOURCE: ISO 4880:1997, 53, modified, — Note 1 to entry and "organic matter to create GR2M" have been added.]

3.2.1.25
detonation
<GR2M> ignition of a carbon-containing gas that results in the formation of *GR2M* (3.1.1.2) particles.

Note 1 to entry: The GR2M is sometimes produced as a by-product of the process to create another material, such as hydrogen.

3.2.2 Nanoribbon production

3.2.2.1
carbon nanotube unzipping
method to produce a graphene *nanoribbon* (3.1.1.7) by splitting a carbon nanotube along its long axis

3.2.2.2
templated growth on SiC
method to produce a graphene *nanoribbon* (3.1.1.7) using a long narrow mask and subsequent *growth on silicon carbide* (3.2.1.9)

3.2.2.3
templated CVD growth
method to produce a graphene *nanoribbon* (3.1.1.7) using a long narrow mask and *CVD* (3.2.1.3)

3.2.2.4
bottom-up precursor growth
method to produce a graphene *nanoribbon* (3.1.1.7) using surface-assisted coupling of molecular precursors and subsequent cyclodehydrogenation

3.2.2.5
electron beam lithographic patterning
method to produce a graphene *nanoribbon* (3.1.1.7) 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* (3.1.1.7) 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 18115-2:2021, 3.1.30]

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 can 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 whether excessive tip wear occurs.

[SOURCE: ISO 18115-2:2021, 3.1.2]

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 18115-2:2021, 3.1.34]

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 80004-6:2021, 4.5.5]

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 80004-6:2021, 4.5.6]

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 18115-2:2021, 5.128 and 5.129, modified — Definitions have been combined and reworded.]

3.3.1.7
photoluminescence spectroscopy
PL spectroscopy
spectroscopy of adsorbed and re-radiated photons

[SOURCE: ISO/TS 80004-6:2021, 5.4]

3.3.1.8
X-ray diffraction
XRD
technique 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, and phase composition of materials incorporating nano-objects.

[SOURCE: ISO/TS 80004-6:2021, 6.3.1]

3.3.1.9
low energy electron microscopy
LEEM
method that examines surfaces where either images or diffraction patterns of the surfaces, or both, 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/TS 80004-6:2021, 4.5.8]

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.

3.3.1.11
Brunauer–Emmett–Teller method
BET method
method for the determination of the total specific external and internal surface area of disperse powders and/or porous solids by measuring the amount of physically adsorbed gas utilizing the model developed by Brunauer, Emmett and Teller for interpreting gas adsorption isotherms

Note 1 to entry: The method originates from Reference [13].

Note 2 to entry: The BET method is applicable only to adsorption isotherms of type II (disperse, nonporous or macroporous solids) and type IV (mesoporous solids, pore diameter between 2 nm and 50 nm). Inaccessible pores are not detected. The BET method cannot reliably be applied to solids that absorb the measuring gas.

[SOURCE: ISO/TS 80004-6:2021, 4.6.3]

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 80004-6:2021, 5.16]

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 80004-6:2021, 5.19]

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 80004-6:2021, 5.14]

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 80004-6:2021, 5.22]

3.3.2.5

thermo gravimetric analysis
TGA

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 80004-6:2021, 6.1.2]

3.3.2.6

inductively coupled plasma mass spectrometry
ICP-MS

analytical technique comprising a sample introduction system, an inductively coupled plasma source for ionization of the analytes, a plasma or vacuum interface and a mass spectrometer comprising an ion focusing, separation and detection system

[SOURCE: ISO/TS 80004-6:2021, 5.23]

3.3 Electrical characterization methods

3.3.3.1

four-terminal sensing
four point probe method

method to measure electrical *sheet* (3.1.1.4) resistance, impedance or conductivity of thin films that uses separate pairs of current-carrying and voltage-sensing electrodes

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

3.3.3.2

graphene Hall bar setup

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 18115-2:2021, 3.1.12]

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.

Note 2 to entry: Angle-resolved UPS is termed ARPES.

[SOURCE: ISO 18115-1:2023, 11.8]

3.3.3.5

angle resolved photoemission spectroscopy

ARPES

UPS method (3.3.3.4) in which the angular distribution of photoelectrons emitted 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* (3.1.1.4) 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: This method is fast and non-contacting.

3.3.3.8

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.

[SOURCE: IEC/TS 62607-6-10:2021, 3.3.1]

3.3.3.9

eddy current measurement

method to measure the induced current circulating along closed paths within a substance

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* (3.1.1.8)

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* (3.1.1.8) 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 in the position of atoms relative to one another from a repeating lattice in a *2D material* (3.1.1.1)

3.4.1.10
level of disorder

<GR2M, Raman spectroscopy> quantification of the disorder present in a *GR2M* (3.1.1.2) given by the ratio of the Raman D peak and G peak intensities as measured by Raman spectroscopy, representing a combination of the amount, size and type of defects

Note 1 to entry: This can be method dependant where different instrument configurations can give different results.

Note 2 to entry: The peak intensities can be measured using area or height depending on which is most relevant.

3.4.1.11
alignment

<2D material> description of the form of stacking between 2D *layers* (3.1.1.8)

Note 1 to entry: Examples are *Bernal stacking* (3.4.1.12), *rhombohedral stacking* (3.4.1.13), *turbostratic stacking* (3.4.1.15).

3.4.1.12
Bernal stacking
AB stacking
hexagonal stacking

<2D material> stacking of *2D material* (3.1.1.1) *layers* (3.1.1.8) 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.

3.4.1.13
rhombohedral stacking
ABC stacking
<2D material> stacking of *2D material* (3.1.1.1) *layers* (3.1.1.8) 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 can 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.

3.4.1.14
stacking angle
<2D material> angle measured in the horizontal plane between the orientations of two *layers* (3.1.1.8) of a *2D material* (3.1.1.1) that are stacked vertically on top of one another

3.4.1.15
turbostratic stacking
<2D material> stacking of *layers* (3.1.1.8) of *2D materials* (3.1.1.1) that cannot be described as *Bernal* (3.4.1.12) or *rhombohedral stacking* (3.4.1.13), instead having a relative *stacking angle* (3.4.1.14) 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).

3.4.1.16
magic angle
<graphene> stacking angle of 1,1° between two graphene layers to exhibit new electronic properties, namely superconductivity

Note 1 to entry: Two graphene layers at this angle can be considered *twisted bilayer graphene* (3.1.2.8) with a *stacking angle* (3.4.1.14) of 1,1°.

Note 2 to entry: This creates a moiré pattern that repeats over a length scale much longer than that of the graphene's crystal structure.

3.4.1.17
domain size
<2D material> lateral dimensions of a single coherent crystalline region within a *layer* (3.1.1.8) 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).

3.4.1.18
lateral size
flake size
<2D material> lateral dimensions of a *2D material* (3.1.1.1) *flake* (3.1.1.3)

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.

3.4.1.19
buffer layer

<2D material> *layer* (3.1.1.8) of material between the substrate and the *2D material* (3.1.1.1) displaying the desired properties

Note 1 to entry: The buffer layer often possesses 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.

3.4.1.20
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 18115-1:2023, 5.16]

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, 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 is typically via substitution of atoms in the lattice.

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* (3.1.1.8) 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
AES	Auger electron spectroscopy
AFM	atomic force microscopy
ALD	atomic layer deposition
ARPES	angle resolved photoemission spectroscopy
BET method	Brunauer–Emmett–Teller method
CVD	chemical vapour deposition
EDS	energy-dispersive X-ray spectroscopy
EDX	energy-dispersive X-ray spectroscopy
EELS	electron energy loss spectroscopy
FL	few-layer
FLG	few-layer graphene
GNP	graphene nanoplatelet
GO	graphene oxide