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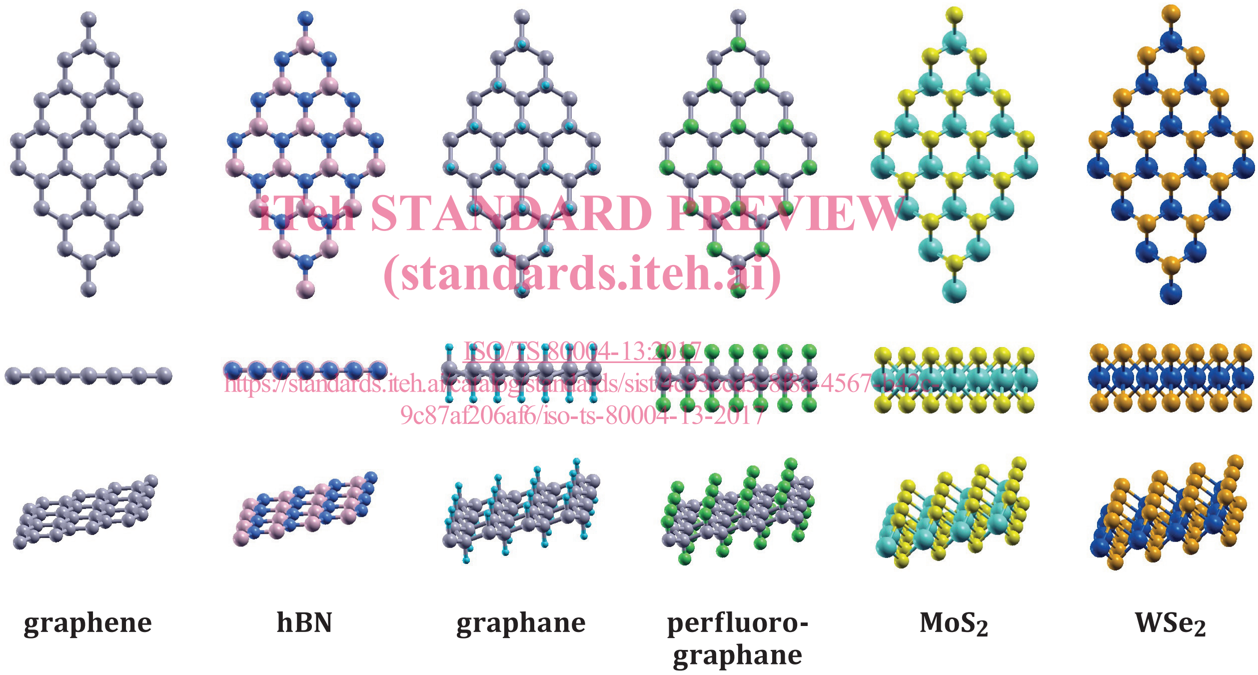
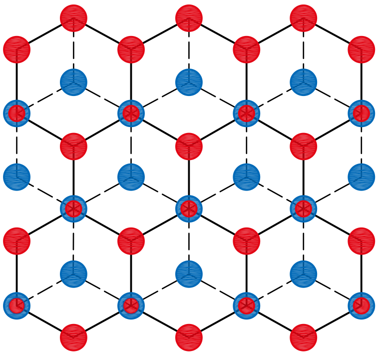
A list of all parts in the ISO 80004 series can be found on the ISO website.

Introduction

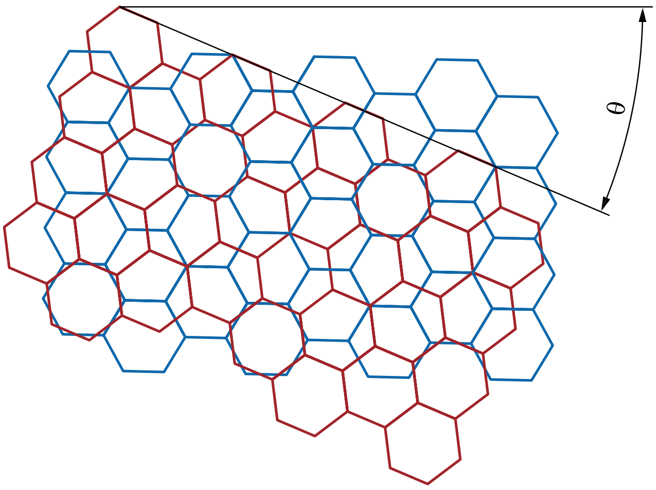
Over the last decade, huge interest has arisen in graphene both scientifically and commercially, due to the many exceptional properties associated with this material, properties such as the electrical and thermal conductivity. More recently, other materials with a structure similar to that of graphene 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.