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**Nanotechnologies — Vocabulary —  
Part 8:  
Nanomanufacturing processes**

*Nanotechnologies — Vocabulaire —  
Partie 8: Processus de nanofabrication*

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## Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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 ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2. [www.iso.org/directives](http://www.iso.org/directives)

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received. [www.iso.org/patents](http://www.iso.org/patents)

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the WTO principles in the Technical Barriers to Trade (TBT) see the following URL: [Foreword - Supplementary information](#)

ISO/TS 80004-8 was prepared jointly by Technical Committee ISO/TC 229, *Nanotechnologies*, and Technical Committee IEC/TC 113, *Nanotechnology standardization for electrical and electronic products and systems*.

Documents in the 80000 to 89999 range of reference numbers are developed by collaboration between ISO and IEC.

ISO/TS 80004 consists of the following parts, under the general title *Nanotechnologies — Vocabulary*:

- *Part 1: Core terms*
- *Part 3: Carbon nano-objects*
- *Part 4: Nanostructured materials*
- *Part 5: Nano/bio interface*
- *Part 6: Nano-object characterization*
- *Part 7: Diagnostics and therapeutics for healthcare*
- *Part 8: Nanomanufacturing processes*

The following parts are under preparation:

- *Part 2: Nano-objects: Nanoparticle, nanofibre and nanoplate<sup>1)</sup>*
- *Part 9: Nano-enabled electrotechnical products and systems*
- *Part 10: Nano-enabled photonic components and systems*
- *Part 11: Nanolayer, nanocoating, nanofilm, and related terms*
- *Part 12: Quantum phenomena in nanotechnology*

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1) Revises and replaces ISO/TS 27687<sup>[5]</sup>.

Graphene and other two-dimensional materials is to form the subject of a future part 13.

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## Introduction

Nanomanufacturing is the essential bridge between the discoveries of the nanosciences and real-world nanotechnology products.

Advancing nanotechnology from the laboratory into volume production ultimately requires careful study of manufacturing process issues including product design, reliability and quality, process design and control, shop floor operations, supply chain management, workplace safety and health practices during the production, use, and handling of nanomaterials. Nanomanufacturing encompasses directed self assembly and assembly techniques, synthetic methodologies, and fabrication processes such as lithography and biological processes. Nanomanufacturing also includes bottom-up directed assembly, top-down high resolution processing, molecular systems engineering, and hierarchical integration with larger scale systems. As dimensional scales of materials and molecular systems approach the nanoscale, the conventional rules governing their behaviour may change significantly. As such, the behaviour of a final product is enabled by the collective performance of its nanoscale building blocks.

Biological process terms are not included in this first edition of the nanomanufacturing vocabulary, but considering the rapid development of the field, it is expected that terms in this important area will be added in a future update to this Technical Specification or in companion documents in the 80004 series. This could include both the processing of biological nanomaterials and the use of biological processes to manufacture materials at the nanoscale.

Similarly, additional terms from other developing areas of nanomanufacturing, including composite manufacturing, roll-to-roll manufacturing, and others, will be included in future documents.

There is a distinction between the terms nanomanufacturing and nanofabrication. Nanomanufacturing encompasses a broader range of processes than does nanofabrication. Nanomanufacturing encompasses all nanofabrication techniques and also techniques associated with materials processing and chemical synthesis.

This document provides an introduction to processes used in the early stages of the nanomanufacturing value chain, namely the intentional synthesis, generation or control of nanomaterials, including fabrication steps in the nanoscale. The nanomaterials that result from these manufacturing processes are distributed in commerce where, for example, they may be further purified, be compatibilized to be dispersed in mixtures or composite matrices, or serve as integrated components of systems and devices. The nanomanufacturing value chain is, in actuality, a large and diverse group of commercial value chains that stretch across these sectors:

- the semiconductor industry (where the push to create smaller, faster, and more efficient microprocessors heralded the creation of circuitry less than 100 nm in size);
- electronics and telecommunications;
- aerospace, defence, and national security;
- energy and automotive;
- plastics and ceramics;
- forest and paper products;
- food and food packaging;
- pharmaceuticals, biomedicine, and biotechnology;
- environmental remediation;
- clothing and personal care.

There are thousands of tonnes of nanomaterials on the market with end use applications in several of these sectors, such as carbon black and fumed silica. Nanomaterials which are rationally designed with

specific purpose are expected to radically change the landscape in areas such as biotechnology, water purification, and energy development.

The majority of sections in this document are organized by process type. In the case of [section 6](#), the logic of placement is as follows: in the step before the particle is made, the material itself is in a gas/liquid/solid phase. The phase of the substrate or carrier in the process does not drive the categorization of the process. As an example, consider iron particles that are catalysts in a process by which you seed oil with iron particles, the oil vaporizes and condenses forming carbon particles on the iron particles. What vaporizes is the oil, and therefore it is a gas phase process. Nanotubes grown from the gas phase, starting with catalyst particles that react with the gas phase to grow the nanotubes, thus this is characterized as a gas process. Indication of whether synthesis processes are used to manufacture nano-objects, nanoparticles, or both, is provided in [Annex A](#).

A common understanding of the terminology used in practical applications will enable communities of practice in nanomanufacturing and will advance nanomanufacturing strength worldwide. Extending the understanding of terms across the existing manufacturing infrastructure will serve to bridge the transition between the innovations of the research laboratory and the economic viability of nanotechnologies.

For informational terms supportive of nanomanufacturing terminology, see Reference [\[1\]](#).

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# Nanotechnologies — Vocabulary —

## Part 8: Nanomanufacturing processes

### 1 Scope

This Technical Specification gives terms and definitions related to nanomanufacturing processes in the field of nanotechnologies. It forms one part of multi-part terminology and definitions documentation covering the different aspects of nanotechnologies.

All the process terms in this document are relevant to nanomanufacturing. Many of the listed processes are not exclusively relevant to the nanoscale. Depending on controllable conditions, such processes may result in material features at the nanoscale or, alternatively, larger scales.

There are many other terms that name tools, components, materials, systems control methods or metrology methods associated with nanomanufacturing that are beyond the scope of this document.

### 2 Terms and definitions from other parts of ISO/TS 80004

The terms and definitions in this clause are given in other parts of ISO/TS 80004. They are reproduced here for context and better understanding.

#### 2.1

##### **carbon nanotube**

##### **CNT**

*nanotube* (2.9) composed of carbon

Note 1 to entry: carbon nanotubes usually consist of curved graphene layers, including single-wall carbon nanotubes and multiwall carbon nanotubes.

[SOURCE: ISO/TS 80004-3:2010, 4.3.]

#### 2.2

##### **nanocomposite**

solid comprising a mixture of two or more phase-separated materials, one or more being nanophase

Note 1 to entry: Gaseous nanophases are excluded (they are covered by nanoporous material).

Note 2 to entry: Materials with *nanoscale* (2.7) phases formed by precipitation alone are not considered to be nanocomposite materials.

[SOURCE: ISO/TS 80004-4:2011, 3.2.]

#### 2.3

##### **nanofibre**

nano-object with two similar external dimensions in the *nanoscale* (2.7) and the third dimension significantly larger

Note 1 to entry: A nanofibre can be flexible or rigid.

Note 2 to entry: The two similar external dimensions are considered to differ in size by less than three times and the significantly larger external dimension is considered to differ from the other two by more than three times.

Note 3 to entry: The largest external dimension is not necessarily in the *nanoscale* (2.7).

[SOURCE: ISO/TS 27687:2008, 4.3.]

## 2.4

### **nanomaterial**

material with any external dimension in the *nanoscale* (2.7) or having internal structure or surface structure in the nanoscale

Note 1 to entry: This generic term is inclusive of *nano-object* (2.5) and *nanostructured material* (2.9).

Note 2 to entry: See also engineered nanomaterial, manufactured nanomaterial and incidental nanomaterial

[SOURCE: ISO/TS 80004-1:2010, 2.4.]

## 2.5

### **nano-object**

material with one, two or three external dimensions in the *nanoscale* (2.7)

Note 1 to entry: Generic term for all discrete nano-objects.

[SOURCE: ISO/TS 80004-1:2010, 2.5.]

## 2.6

### **nanoparticle**

*nano-object* (2.5) with all three external dimensions in the *nanoscale* (2.7)

Note 1 to entry: if the lengths of the longest to the shortest axes of the *nano-object* (2.5) differ significantly (typically by more than three times), the terms *nanofibre* (2.3) or *nanoplate* are intended to be used instead of the term nanoparticle.

[SOURCE: ISO/TS 27687:2008, 4.1.]

## 2.7

### **nanoscale**

size range from approximately 1 nm to 100 nm

Note 1 to entry: Properties that are not extrapolations from a larger size will typically, but not exclusively, be exhibited in this size range. For such properties the size limits are considered approximate.

Note 2 to entry: The lower limit in this definition (approximately 1 nm) is introduced to avoid single and small groups of atoms from being designated as *nano-objects* (2.5) or elements of nanostructures, which might be implied by the absence of a lower limit.

[SOURCE: ISO/TS 80004-1:2010, 2.1.]

## 2.8

### **nanostructured material**

material having internal or surface structure in the *nanoscale* (2.7)

Note 1 to entry: If external dimensions are in the nanoscale, the term *nano-object* (2.4) is recommended.

Note 2 to entry: Adapted from ISO/TS 80004-1:2010, definition 2.7.

[SOURCE: ISO/TS 80004-4, 2.11.]

## 2.9

### **nanotube**

hollow *nanofibre* (2.3)

[SOURCE: ISO/TS 27687:2008, 4.4]

### 3 General terms

#### 3.1

##### **bottom up nanomanufacturing**

processes that use small fundamental units in the *nanoscale* (2.7) to create larger functionally rich structures or assemblies

#### 3.2

##### **co-deposition**

simultaneous deposition of two or more source materials

Note 1 to entry: Common methods include vacuum, thermal spray, electrodeposition and liquid suspension deposition techniques.

#### 3.3

##### **communion**

crushing or grinding for particle size reduction

#### 3.4

##### **directed assembly**

<nanotechnologies> formation of a structure guided by external intervention using components at the *nanoscale* (2.7) that can, in principle, have any defined pattern

#### 3.5

##### **directed self-assembly**

*self-assembly* (3.11) influenced by external intervention to produce a preferred structure, orientation or pattern

Note 1 to entry: Examples of external intervention include an applied field, a chemical or structural template, chemical gradient, and fluidic flow.

#### 3.6

##### **lithography**

reproducible creation of a pattern

Note 1 to entry: The pattern can be formed in a radiation sensitive material or by transfer of material onto a substrate either by transfer, by printing or by direct writing.

#### 3.7

##### **multilayer deposition**

alternating deposition of two or more source materials to produce a composite layer structure

#### 3.8

##### **nanofabrication**

ensemble of activities, to intentionally manufacture devices in the *nanoscale* (2.7), for commercial purpose

#### 3.9

##### **nanomanufacturing**

intentional synthesis, generation or control of nanomaterials, or fabrication steps in the *nanoscale* (2.7), for commercial purpose

[SOURCE: ISO/TS 80004-1:2010, definition 2.11.]

#### 3.10

##### **nanomanufacturing process**

ensemble of activities to intentionally synthesize, generate or control *nanomaterials* (2.4), or fabrication steps in the *nanoscale* (2.7), for commercial purpose

[SOURCE: ISO/TS 80004-1:2010, 2.12.]

**3.11**

**self-assembly**

autonomous action by which components organize themselves into patterns or structures

**3.12**

**surface functionalization**

chemical process that acts upon a surface to impart a selected chemical or physical functionality

**3.13**

**top-down nanomanufacturing**

processes that create structures at the *nanoscale* (2.7) from macroscopic objects

**4 Directed assembly**

**4.1**

**electrostatic driven assembly**

<nanotechnologies> use of electrostatic force to orient or place *nanoscale* (2.7) elements in a device or material

**4.2**

**fluidic alignment**

<nanotechnologies> use of fluid flow to orient *nanoscale* (2.7) elements in a device or material

**4.3**

**hierarchical assembly**

<nanotechnologies> use of more than one type of *nanomanufacturing* (3.9) process to control structure at multiple length scales

**4.4**

**magnetic driven assembly**

<nanotechnologies> use of magnetic force to assemble at the *nanoscale* (2.7) in a desired pattern or configuration

**4.5**

**shape-based assembly**

<nanotechnologies> use of geometric shapes of *nanoparticles* (2.6) to achieve a desired pattern or configuration

**4.6**

**supramolecular assembly**

use of non-covalent chemical bonding to assemble molecules or *nanoparticles* (2.6) with surface ligands

**4.7**

**surface-to-surface transfer**

<nanotechnologies> transfer of *nanoparticles* (2.6) or structures from the surface of one substrate, on which they have been deposited, grown or assembled, onto another substrate

**5 Self-assembly processes**

**5.1**

**colloidal crystallization**

<nanotechnologies> sedimentation of *nanoparticles* (2.6) from a solution to form a solid which consists of a close-packed, ordered array of repeating units

**5.2****graphioepitaxy**

<nanotechnologies> *directed self-assembly* (3.5) using *nanoscale* (2.7) topographical features

Note 1 to entry: Includes the growth of a thin layer on the surface and growth of an additional layer on top of a substrate which has the same or different structure as the underlying crystal.

**5.3****ion beam surface reconstruction**

<nanotechnologies> use of an accelerated ion beam to cause surface modification which may be at the *nanoscale* (2.7)

**5.4****Langmuir-Blodgett film formation**

creation of a molecular monolayer at an air-liquid interface using a Langmuir-Blodgett trough

**5.5****Langmuir-Blodgett film transfer**

transfer of a Langmuir-Blodgett molecular monolayer formed at an air-liquid interface onto a solid surface by dipping a solid substrate into the supporting liquid

**5.6****layer-by-layer deposition****LbL deposition**

electrostatic process of depositing polyelectrolytes with opposite charges laid over or under another

**5.7****modulated elemental reactant method**

use of vapour deposited precursors with regions of controlled composition as a template for the formation of interleaved layers of two or more structures

**5.8****self-assembled monolayer formation****SAM formation**

spontaneous formation of an organized molecular layer on a solid surface from solution or the vapour phase, driven by molecule-to-surface bonding and weak intermolecular interaction

**5.9****Stranski-Krastanow growth**

mode of thin film growth in which both layer and island formation mechanisms are present

**6 Synthesis****6.1 Gas process phase — Physical methods****6.1.1****cold gas dynamic spraying**

to fluidize either *nanoscale* (2.7) crystalline powders or conventional powders that are then consolidated onto a surface coating in a high velocity inert gas

**6.1.2****electron-beam evaporation**

process in which a material is vaporized by incidence of high energy electrons in high or ultra-high vacuum conditions for subsequent deposition onto a substrate

### 6.1.3 Electro-spark deposition processes

#### 6.1.3.1

##### **electro-spark deposition**

pulsed-arc micro-welding process using short-duration, high-current electrical pulses to deposit an electrode material on a substrate

### 6.1.4 Spray drying processes

#### 6.1.4.1

##### **freeze drying**

dehydration or solvent removal by rapid cooling immediately followed by vacuum sublimation

#### 6.1.4.2

##### **spray drying**

producing a dry powder from a liquid or slurry by rapid removal of liquid droplets via contact with a hot gas

#### 6.1.5

##### **supercritical expansion**

precipitation of *nano-objects* (2.5) resulting from an expansion of a solution above its critical temperature ( $T_C$ ) and critical pressure ( $P_C$ ) through a spray device

#### 6.1.6

##### **suspension combustion thermal spray**

*thermal spray* (7.2.16) in which the precursor is introduced to a plasma jet in the form of a liquid suspension

#### 6.1.7

##### **wire electric explosion**

formation of *nanoparticles* (2.6) by applying an electrical pulse of high current density through a wire causing it to volatilize with subsequent recondensation

#### 6.1.8

##### **vaporization**

process of assisted change of phase from solid or liquid to gas or plasma phases

Note 1 to entry: Vaporization process is often used to consequently deposit the vaporized material on a target substrate. The whole process is known as PVD (ISO 2080:2008, 2.12)[2].

Note 2 to entry: High Vacuum PVD is usually performed at pressures in the range of  $10^{-6}$  to  $10^{-9}$  Torr. Ultra-High Vacuum (UHV PVD) is the deposition performed at pressures below  $10^{-9}$  Torr.

## 6.2 Gas process phase — Chemical methods

### 6.2.1 Flame synthesis processes

#### 6.2.1.1

##### **liquid precursor combustion**

creation of solid product, typically a *nanomaterial* (2.4) in aggregate form, via exothermic reaction of a feedstock solution with an oxidizer

[SOURCE: ISO 19353, 3.3, modified.]

#### 6.2.1.2

##### **plasma spray**

creation of a jet of solid product, typically a *nanomaterial* (2.4) in aggregate form from an ionized gaseous source

**6.2.1.3****pyrogenesis**

using combustion or other heat source to produce solid product, typically a *nanomaterial* (2.4) in aggregate form facilitated by an aerosolized spray

**6.2.1.4****solution precursor plasma spray**

gas phase process in which a thermal (equilibrium) plasma is formed into which a solution containing precursors is introduced resulting in gaseous species that during cooling form a solid product, typically a *nanomaterial* (2.4) in aggregate form

**6.2.1.5****thermal spray pyrolysis**

creation of solid product, typically a *nanomaterial* (2.4) in aggregate form from liquid precursors through liquid atomization and reaction using a thermal source

**6.2.2****hot wall tubular reaction**

*chemical vapour deposition* (7.2.3) performed in a tubular furnace in which the reaction surface is maintained at a controlled elevated temperature

**6.2.3****photothermal synthesis**

gas phase process where a precursor or other gaseous species is heated by absorption of infrared radiation resulting in heating of the gas and thermal decomposition of the precursor producing a solid product, typically a *nanoparticle* (2.6)

**6.2.4****vapour-liquid-solid nanofibre synthesis****VLS**

growth of *nanofibres* (2.3) onto a substrate with feed material in gaseous form in the presence of a liquid catalyst

Note 1 to entry: The VLS method for fibres exploits a liquid phase on the end of a fibre which can rapidly adsorb a vapour to supersaturation levels, and from which crystal growth subsequently occurs.

**6.3 Liquid process phase — Physical methods****6.3.1****electrospinning**

use of electrical potential to induce drawing of fine fibres from a liquid phase

**6.3.2*****in-situ* intercalative polymerization**

insertion of monomers into layered inorganic materials followed by polymerization which result in *nanocomposites* (2.2)

**6.3.3****nanoparticle dispersion**

creating a suspension of *nanoparticles* (2.6) in a liquid through molecular ligands, surface charges or other interactions to prevent or slow sedimentation

**6.3.5****tape casting**

deposition of macroscopic layer by spreading slurry of ceramic paste onto a flat surface

Note 1 to entry: *Nanoparticles* (2.6) may be part of the composition of the layer.

### 6.3.6

#### **wet ball milling**

*grinding* (6.5.5) process in liquid via rolling feedstock material with crushing balls of greater hardness to create a force of impact in order to reduce the size of target components

Note 1 to entry: The product of the process is known as slurry.

## 6.4 Liquid process phase — Chemical methods

### 6.4.1

#### **acid hydrolysis of cellulose**

use of an acid to release nanocrystalline cellulose from cellulose

### 6.4.2

#### **nanoparticle precipitation**

formation of *nanoparticles* (2.6) from solution reactions where particle size may be controlled by kinetic factors

### 6.4.3

#### **prompt inorganic condensation**

formation of atomically smooth and dense films by *spin-coating* (7.2.17) and low-temperature curing of organic free aqueous solutions based on organometallic molecular precursors

### 6.4.4

#### **reverse micelle process**

synthesis of *nanoparticles* (2.6) in solution using reagents in the presence of reaction stopping ligands that attach to the nanoparticle surface and inhibit further growth

### 6.4.5

#### **sol-gel processing**

conversion of a chemical solution or colloidal suspension (sol) to an integrated network (gel), which can then be further densified

### 6.4.6

#### **surfactant templating**

use of surfactants to self-assemble molecular species such that they can be subsequently solidified in a structured configuration at the *nanoscale* (2.7)

EXAMPLE MCM 41.

### 6.4.7

#### **Stober process**

generation of particles of silicate by using a tetra-alkyl orthosilicate and a combination of low molecular weight alcohol and ammonia, used with or without water

Note 1 to entry: This is a *sol-gel processing* (6.4.5) method for synthesizing silica.

## 6.5 Solid process phase — Physical methods

### 6.5.1 Block copolymer processes

#### 6.5.1.1

##### **block copolymer phase segregation**

formation of repeatable 2D and 3D structures from the segregation of immiscible polymer chain segments

#### 6.5.1.2

##### **block copolymer templating**

incorporation of a material into the phase of a block copolymer to achieve *nanoscale* (2.7) structure

**6.5.2****clay dispersion**

mixing of clay particles into a liquid matrix, usually polymeric, which is then solidified to produce a clay composite

**6.5.3****cold pressing**

<nanotechnologies> pressing particles at the *nanoscale* (2.7) with applied pressure to fuse and create density

**6.5.4****conshearing continuous confined strip shearing****C2S2**

use of very large plastic strain to produce grains in a bulk metal without any significant change in the overall dimensions

Note 1 to entry: The main objective is to produce lightweight parts with greatly improved mechanical properties.

**6.5.5****devitrification**

structural transformation from a glassy state to a crystalline state that introduces *nanoscale* (2.7) voids or structure

**6.5.6****grinding**

<nanotechnologies> creation of *nanoparticles* (2.6) via mechanical shearing in contact with a material of greater hardness

**6.5.7****high-speed micromachining**

creating precise two and three dimensional workpieces from the bulk or on the surface of an object or material by cutting using defined geometry cutting tools

Note 1 to entry: Precision is achieved through high cutting spindle speeds usually between 30 000 and 100 000 r/min.

Note 2 to entry: Laser, e-beam, ion beam, ultrasound, milling and CNC machining can be used.

Note 3 to entry: Definition of high speed varies with each specific technology.

**6.5.8****ion implantation**

use of incident flux high energy ions to modify the surface material by damage and recrystallization

**6.5.9 Milling processes****6.5.9.1****cryogenic milling**

*grinding* (6.5.5) under cryogenic temperatures (below  $-150\text{ }^{\circ}\text{C}$ ,  $-238\text{ }^{\circ}\text{F}$  or  $123\text{ K}$ )

**6.5.9.2****dry ball milling**

<nanotechnologies> creation of *nanoparticles* (2.6) via rolling feedstock material with crushing balls of greater hardness to mix two or more immiscible nanoparticles which are then heated to sinter them

[SOURCE: ISO 11074:2005, ISO 3252:1999, modified.]

**6.5.10****multi-pass coin forging**

production of *nanoscale* (2.7) grain structures using severe plastic deformation by mechanical pressing a sheet of material between two sine shaped dies with successive rotation of the workpiece followed by flat forging or rolling

**6.5.11**

**nanotemplated growth**

deposition from solution or vapour phase of material into *nanoscale* (2.7) confined spaces to form *nanoparticles* (2.6) or *nanostructured materials* (2.8)

**6.5.12**

**polymer nanoparticle dispersion**

mixing of *nanoparticles* (2.6) into a liquid polymer matrix which is solidified to produce a polymer matrix nanoparticle composite

**6.5.13 Sintering processes**

**6.5.13.1**

**hot pressing**

high-pressure powder metallurgy process for forming hard and brittle materials at high temperatures

Note 1 to entry: Pressures of up to 50 MPa (7 300 psi) and temperatures of typically 2 400 °C (4 350 °F) may be used.

**6.5.13.2**

**nanoparticle sintering**

joining of particles and increasing their contact interfaces by atom movement within and between the particles due to the application of heat

[SOURCE: ISO 836:2001.]

**6.5.13.3**

**spark plasma sintering**

densifying powders under mechanical pressure by applying DC pulsed currents to conducting powders at a very high heating or cooling rate (up to 1 000 K/min), avoiding coarsening the internal structure

**6.6 Solid process phase — Chemical methods**

**6.6.1**

**block copolymer chemical derivatization**

modification of block copolymer solid through the addition of atoms or molecules that selectively bind or segregate to only one phase

**6.6.2**

**electrochemical anodization**

<nanotechnologies> a process in which the anode is simultaneously oxidized and etched, resulting in *nanoscale* (2.7) pores usually with a high degree of regularity and controllability

Note 1 to entry: This process may also be referred to as anodic etching.

**6.6.3**

**intercalation**

process that inserts heterogeneous material (atoms, small molecules) into a host structure (crystal lattice or other macromolecular structure)

**6.6.4**

**two-phase methods**

heating and then rapid cooling binary mixture of materials to produce a solid composite with *nanoscale* (2.7) features

## 7 Fabrication

### 7.1 Nanopatterning lithography

#### 7.1.1

##### **3D lithography**

process in which patterns or structuring can be achieved with *nanoscale* (2.7) dimensions in all three dimensions

#### 7.1.2

##### **additive processing**

adding a layer of new material, in order to leave a pattern of deposited material on the substrate

Note 1 to entry: Two terms are used to describe additive processing using resist: lift-off and stencil. In lift-off the layer of new material is applied to the whole surface, the pattern is revealed after the removal of the unexposed resist with the overlaid material; with a stencil the new material is only added where the surface is not protected by resist [as with *electrodeposition* (7.2.4) with a resist layer in place].

#### 7.1.3

##### **block copolymer lithography**

use of microphase separation in diblock copolymers to create polymer templates with *nanoscale* (2.7) patterns

#### 7.1.4

##### **colloidal crystal template lithography**

use of crystallized colloidal particles to create a 2D or 3D framework for subsequent deposition or etching

#### 7.1.5

##### **deep ultraviolet lithography**

##### **DUV**

patterned exposure of a photoactive polymer using ultraviolet light in the wavelength range 100 nm to 280 nm

#### 7.1.6

##### **dip-pen nanolithography**

method in which a scanning tip is used to transfer specific material onto a substrate surface, via a solvent meniscus, for patterning a substrate at length scales below 100 nm

Note 1 to entry: Often the tip is an AFM tip coated with specific molecules that are to be deposited on the surface in a layer that can be a monolayer. In other cases, the material to be deposited could be *nanoparticles* (2.6).

Note 2 to entry: "Dip-Pen Nanolithography" is the trade name of a product supplied by NanoInk Inc. This information is given for the convenience of users of this document and does not constitute an endorsement by ISO of the product named. Equivalent products may be used if they can be shown to lead to the same results.

[SOURCE: ISO 18115-2:2010, 6.40]

#### 7.1.7

##### **electron-beam lithography**

direct write patterning process that uses a focused, concentrated stream of electrons to modify the solubility of a resist layer

#### 7.1.8

##### **extreme ultraviolet lithography**

##### **EUV**

exposure of a resist material using electromagnetic radiation of approximately 10 nm to 20 nm wavelength

Note 1 to entry: Usually reflective optics are used to focus the radiation.

7.1.9

**focused ion-beam lithography**

**FIB**

direct write patterning process that uses a focused ion beam to modify the solubility of a resist layer

7.1.10

**immersion optics**

optical *lithography* (3.6) process that immerses the objective lens and resist in a liquid to provide refractive index matching

7.1.11

**interference lithography**

use of diffraction gratings to create an interference pattern of radiation to create *nanoscale* (2.7) exposure patterns in resist

7.1.12

**ion induced deposition**

use of a focused, concentrated stream of ions to bring about or give rise to the localized reaction of an adsorbed molecule to deposit material

7.1.13

**ion induced etching**

use of a focused ion beam to induce the localized reaction of an adsorbed molecule to etch the substrate material

7.1.14

**ion projection lithography**

use of accelerated ions in conjunction with a mask to create *nanoscale* (2.7) exposure patterns in resist

7.1.15

**micro-contact printing**

form of soft *lithography* (3.6) in which a soft mould is dipped into an ink and the pattern transferred to a substrate by pressing

Note 1 to entry: The fidelity of the transfer is strongly dependent on the local surface characteristics of the substrate for the particular material used as an ink.

7.1.16

**microfluidic deposition**

use of micrometre scale or *nanoscale* (2.7) channels in a solid manifold to facilitate the transfer of material from a liquid or solution state into a solid state onto a substrate surface

7.1.17

**nano-embossing**

transfer of a pattern using a template into bulk material rather than into a thin film

Note 1 to entry: This definition also includes 3-dimensional patterning.

Note 2 to entry: In embossing, the flow of material displaced by the template is not constrained. The embossed artefact is normally the end product, while in imprinting, the patterned resist is used in subsequent processing.

7.1.18

**nano-imprint lithography**

**NIL**

process in which a pattern is transferred by pressing a *nanoscale* (2.7) template (usually called a die, stamp, mask or mould) of the desired pattern in relief into a deformable resist, which is then cured thermally or with light

Note 1 to entry: As the pattern is defined by the topography of the template it is a printing process and not a primary *lithography* (3.6).

Note 2 to entry: Types of nano-imprint lithography are conveniently divided by the use of a particular type of resist for imprinting. With thermoplastic polymeric materials, the resist is heated so that it can flow when the pressure is applied to the template. With thermosetting resists, heat is applied after the initially liquid resist has been displaced by the template. Negative photosensitive resists can be set by the application of light through the (transparent in this case) template. Processes using photosensitive resist are called by different workers, optical imprinting, optical nano-imprinting or step and flash.

#### 7.1.19

##### **natural lithography**

process in which the primary pattern is defined by the replication of a pattern that occurs in nature

EXAMPLE The stripes that occur on collagen fibres or the pattern formed by strands of RNA. The term refers to the use of a mask or template that does not require the use of a focused beam of radiation to define the pattern.<sup>[12]</sup>

#### 7.1.20

##### **photolithography optical lithography**

process in which electromagnetic radiation is used to transfer a mask through a reticle to create a pattern

Note 1 to entry: Usually a resist material is used to make the mask.

#### 7.1.21

##### **phase-contrast photolithography**

exposure of a resist material through phase-shifting reticles to increase resolution of *nanoscale* (2.7) patterns

#### 7.1.22

##### **plasmonic lithography**

use of *nanoscale* (2.7) metallic patterns to guide near-field optical radiation to create nanoscale photolithographic exposure patterns in resist

#### 7.1.23

##### **scanning force probe writing**

use of an scanning probe microscope (SPM) tip to mark, ink or otherwise locally modify the surface of a substrate

#### 7.1.24

##### **scanning tunnelling microscope chemical vapour deposition**

##### **STM CVD**

application of a voltage to an STM tip to facilitate *nanoscale* (2.7) CVD (7.2.3) in the proximity of the tip onto a substrate

#### 7.1.25

##### **soft lithography**

mechanical printing processes in which an elastomeric (or soft) template is used to transfer the pattern

#### 7.1.27

##### **subtractive processing**

removal of material except where the surface is protected by the patterned resist

#### 7.1.28

##### **x-ray lithography**

process that uses X-ray radiation to expose a mask to create a lithographic pattern

Note 1 to entry: As X-rays are difficult to focus on a *nanoscale* (2.7) sized beam (but see extreme ultraviolet lithography), X-ray lithography is used to refer to a printing process, using a mask that has a pattern that consists of regions opaque and transparent to X-rays. The mask typically consists of a membrane of a material that has low X-ray absorption, with a pattern of highly absorbing material (e.g. a metal). Usually, a resist material is used to make the mask.

## 7.2 Deposition processes

### 7.2.1

#### **adsorption**

retention, by physical or chemical forces, of gas molecules, of dissolved substances, or of liquids by the surfaces of solids or liquids with which they are in contact

[SOURCE: ISO 14532:2001, 2.2.2.7.]

### 7.2.2

#### **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.

### 7.2.3

#### **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 2080:2008, 2.2, modified.]

### 7.2.4

#### **catalytic chemical vapour deposition**

##### **CCVD**

CVD ([7.2.3](#)) based on the decomposition of gaseous molecules in the presence of a catalyst

Note 1 to entry: CCVD is used in the synthesis of carbon *nanotubes* ([2.9](#)) on a substrate from source materials such as hydrocarbons (e.g. methane) with catalysts such as Fe, Ni, or Co.

Note 2 to entry: The term CCVD is redundant with the process of catalysis.

### 7.2.5

#### **cluster beam coating**

deposition of *nanoparticles* ([2.6](#)) to form a solid-structured film using a source beam

### 7.2.6

#### **dip coating**

creation of a thin film by dipping a substrate into a solution containing the material of interest

### 7.2.7

#### **electrodeposition**

electroplating

deposition of material onto an electrode surface from ions in solution due to electrochemical reduction

### 7.2.8

#### **electroless deposition**

autocatalytic deposition of material onto a solid surface from ions in solution in the presence of a soluble reducing agent

### 7.2.9

#### **electro-spray**

deposition of material onto a surface by pressurization through a nozzle held at an applied voltage

### 7.2.10

#### **evaporation**

process in which a material is vaporized by heating in high or ultra-high vacuum conditions for subsequent deposition onto a substrate

**7.2.11****focused electron-beam deposition**

*chemical vapour deposition* (7.2.3) using a focused, concentrated stream of electrons to induce localized reactions of molecules from a precursor gas onto a surface

**7.2.12****focused ion-beam deposition****FIB**

ion induced formation and transfer of a material onto the surface of a substrate

Note 1 to entry: FIB-assisted chemical vapour deposition occurs when a gas, such as tungsten carbonyl ( $W(CO)_6$ ) is introduced to the vacuum chamber and allowed to chemisorb onto the sample. By scanning an area with the beam, the precursor gas will be decomposed into volatile and non-volatile components; the non-volatile component, such as tungsten, remains on the surface as a deposit. This is useful, as the deposited metal can be used as a sacrificial layer, to protect the underlying sample from the destructive sputtering of the beam. Other materials such as platinum can also be deposited.

**7.2.13****molecular beam epitaxy**

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* (2.7) features can be grown in this method by exploiting strain, e.g. InAs dots on GaAs substrate.

Note 3 to entry: Adapted from Reference [13].

**7.2.14****physical vapour deposition****PVD**

process of depositing a coating by vaporizing and subsequently condensing an element or compound, usually in a high vacuum

[SOURCE: ISO 2080, 2.12.]

**7.2.15****polyelectrolyte layer-by-layer****LbL**

repeated alternate deposition of oppositely charged polymers onto a surface

**7.2.16****thermal spray**

<nanotechnologies> deposition of *nanoparticles* (2.6) to form a solid film from a plasma-based or combustion-based nanoparticle source

**7.2.17****spin coating**

creation of a thin film by deposition of a material in solution onto a rotating substrate by utilizing centrifugal force

**7.2.18****spray deposition**

process to deposit material onto the outside or uppermost layer of substrate by pressurization of a liquid through a nozzle to create droplets or aerosols

7.2.19

**sputter deposition**

*physical vapour deposition* (7.2.14) process employing energetic particles to transfer atoms from a target material to a substrate

7.2.20

**surface polymerization**

creation of a polymer film on a surface from vapour phase or liquid phase monomer

7.3 Etching processes

7.3.1

**anisotropic etching**

process in which etch rate in the direction normal to the surface is much higher than in direction parallel to the surface

7.3.2

**Bosch etching**

process that alternates repeatedly between an etching mode and a passivation mode to achieve the etching of nearly vertical structures

7.3.3

**chemical etching**

process of using acids, bases or other chemicals to dissolve away unwanted materials from a substrate

Note 1 to entry: The products of a chemical etch are either soluble in the etch solution (as in wet etching) or volatile at low pressures (as in dry etching).

7.3.4

**chemically assisted ion beam etching**

reactive gases are introduced during etching via needles or gas rings above the substrate

7.3.5

**cryogenic etching**

process in which the substrate is cooled to approximately 163 K to produce nearly vertical etched sidewall structures

Note 1 to entry: The low temperature slows down the chemical reaction that produces isotropic etching. Ions continue to bombard upward-facing surfaces and etch them away producing steep side walls.

7.3.6

**crystallographic etching**

process in which the etch rates are different for different crystallographic directions

7.3.7

**deep reactive ion etching**

**DRIE**

highly anisotropic etch process used to create high aspect ratio structures

EXAMPLE Steep sided holes and trenches.

Note 1 to entry: There are two main technologies for DRIE: *cryogenic etching* (7.3.5) and *Bosch etching* (7.3.2).

7.3.8

**dry-ashing**

form of chemical etching in which surface material is spontaneously etched by a neutral or activated gas and forms volatile etch products

EXAMPLE Photoresist mask removal in an oxygen plasma ambient.

**7.3.9****dry-etching**

process that makes use of partially ionized gases to remove material from a substrate

**7.3.10****focused ion-beam etching****FIB**

beam of ions (usually gallium) focused through a set of electrostatic lenses to create a small spot on the substrate

Note 1 to entry: The beam removes material from the substrate through physical sputtering. The beam spot can be scanned across the surface to create a pattern. *Nanoscale* (2.7) resolution can be obtained in this process.

Note 2 to entry: Also known as FIB milling.

**7.3.11****high-density plasma etching**

*plasma etching* (7.3.18) which uses a high density (typically 1 011 to 1 012 ions per cubic centimetre) ion beam as created by electron cyclotron resonance, helicon, magnetron or inductive methods

Note 1 to entry: Plasma can be used for either etching or deposition depending on the location of the substrate.

**7.3.12****inductive coupled plasma****ICP**

method by which energy is magnetically coupled into the plasma by a current carrying loop around the chamber

**7.3.13****ion beam etching****ion beam milling**

use of a plasma source to produce an ion beam to remove material from a substrate

**7.3.14****isotropic etching**

process (usually wet) in which etch rate in the horizontal and vertical directions are identical

**7.3.15****laser ablation**

using the energy from a pulsed laser to erode material from the surface of a target

Note 1 to entry: Method of producing *nanoscale* (2.7) features on a surface.

**7.3.16****light-assisted etching****photochemical etching**

processes where light is used to influence or control the etching process

Note 1 to entry: Light-assisted etching is based on the photosensitivity of chemical etching under certain conditions. A desired lateral structure can be produced, depending on the illumination pattern, which is defined by optical imaging during the etching process. This process has been used to prepare laterally structured luminescent porous silicon for example.

**7.3.17****physical etching****sputter etching**

process of etching through physical interactions (momentum transfer) between accelerated chemically inert ions (e.g. argon) and etched solid

Note 1 to entry: The process is anisotropic, and non-selective.

### 7.3.18

#### **plasma etching**

process that takes place in a gaseous system consisting of ions and electrons formed by an electrical discharge to remove material from a substrate

Note 1 to entry: The term plasma etching machine is usually restricted to a machine with two capacitive electrodes in which the material to be etched is immersed in the plasma.

Note 2 to entry: As the ionization of the gas is rarely complete, there are also neutral species, some in an excited state (radicals) that can participate in the etching.

### 7.3.19

#### **radiation track etching**

formation of a structure by etching along the pathways formed by radiation damage in a solid.

EXAMPLE Porous polymer in which tracks are etched using a selective solvent that only dissolves short chains.

### 7.3.20

#### **reactive ion etching**

##### **RIE**

form of *plasma etching* (7.3.18) in which the wafer is placed on a radio-frequency-driven electrode and the counter electrode has a larger area than the driven electrode

Note 1 to entry: The plasma beam is generated under low pressure by an electromagnetic field. High energy ions, predominantly bombarding the surface normally create a local abundance of radicals that react with the surface. RIE can produce very anisotropic profiles as compared with isotropic profiles produced with *wet etching* (7.3.22).

### 7.3.21

#### **selective etching**

process in which one surface material is removed rapidly while the other is removed very slowly or not removed at all

EXAMPLE HF water solution etches SiO<sub>2</sub> very rapidly while not etching silicon.

### 7.3.22

#### **wet etching**

chemical removal of a surface material with a liquid etchant

## 7.4 Printing and coating

### 7.4.1

#### **embossing**

imprinting

transfer of a pattern by pressing a rolling master template into a deformable bulk material

### 7.4.2

#### **multilayer film process**

<nanotechnologies> creation of a multilayer by bonding individual films together in a rolling process

### 7.4.3

#### **nanofibre precipitation**

precipitation of *nanofibres* (2.3) from solution onto a substrate

### 7.4.4

#### **nanoparticle spray coating**

deposition of *nanoparticles* (2.6) from a solvent, a plasma, a cluster beam or from another nanoparticle source

## Annex A (informative)

### Identification of output resulting from defined synthesis processes

Process phase	Headings	Nanomanufacturing process term to be defined	Nano-object process	Nanostructured material process
Gas physical methods		Cold gas dynamic spraying		✓
		Electron-beam evaporation	✓	
	Electro-spark deposition processes	Electro-spark deposition	✓	
		Photothermal synthesis	✓	
		Solution precursor plasma spray		✓
		Sputtering	✓	
	Spray drying (agglomeration) processes	Freeze drying	✓	
	Spray drying (agglomeration) processes	Spray drying	✓	
		Supercritical expansion	✓	
		Suspension combustion thermal spray	✓	
		Wire electric explosion	✓	
		Vaporization	✓	
	Gas chemical methods		Atomic layer deposition (ALD)	
		Chemical vapour deposition (CVD)	✓	✓
		Catalytic chemical vapour deposition (CCVD)	✓	✓
Flame synthesis (combustion-based) processes		Liquid precursor combustion	✓	✓
Flame synthesis (combustion-based) processes		Plasma spray	✓	
Flame synthesis (combustion-based) processes		Pyrogenesis	✓	✓
Flame synthesis (combustion-based) processes		Thermal spray pyrolysis	✓	✓
		Graphioepitaxy		✓
		Hot wall tubular reactor	✓	✓
		Photothermal synthesis	✓	
		Solution precursor thermal spray	✓	✓
Liquid physical methods		Communion	✓	✓
		Electrospinning	✓	✓
	Size reduction processes in liquid (communion)	<i>In-situ</i> intercalative polymerization	✓	✓
		Nanoparticle dispersion	✓	
		Tape casting		✓
		Wet ball milling	✓	✓

Process phase	Headings	Nanomanufacturing process term to be defined	Nano-object process	Nanostructured material process
<b>Liquid chemical methods</b>		Acid hydrolysis of cellulose	√	
		Nanoparticle precipitation	√	
		Prompt inorganic condensation	√	
		Reverse micelle process	√	√
		Sol-gel processing	√	√
		Surfactant templating	√	
		Stober process	√	√
<b>Solid physical methods</b>	Severe plastic deformation processes	High pressure torsion		√
	Block copolymer processes	Block copolymer chemical derivatization		√
	Block copolymer processes	Block copolymer phase segregation		√
	Block copolymer processes	Block copolymer templating		√
		Cold pressing		√
		Conshearing continuous confined strip shearing		√
		Devitrification		√
		Grinding	√	
		High-speed micromachining		√
		Ion implantation		√
	Milling processes	Cryogenic milling	√	
		Dry ball milling	√	
		Multi-pass coin forging	√	
		Nanotemplated growth	√	√
	Sintering processes	Hot pressing		√
		Nanoparticle sintering	√	
		Spark plasma sintering	√	√
<b>Solid chemical methods</b>		Clay dispersion		√
		Electrochemical anodization		√
		Intercalation	√	√
		Polymer nanoparticle dispersion		√
		Two-phase methods		√

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