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TECHNICAL REPORT

IEC nanoelectronics standardization roadmap

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

IEC NANOELECTRONICS STANDARDIZATION ROADMAP

FOREWORD

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IEC 62834, which is a technical report, has been prepared by IEC technical committee 113: Nanotechnology standardization for electrical and electronic products and systems.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
113/161/DTR	113/197/RVC

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

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

INTRODUCTION

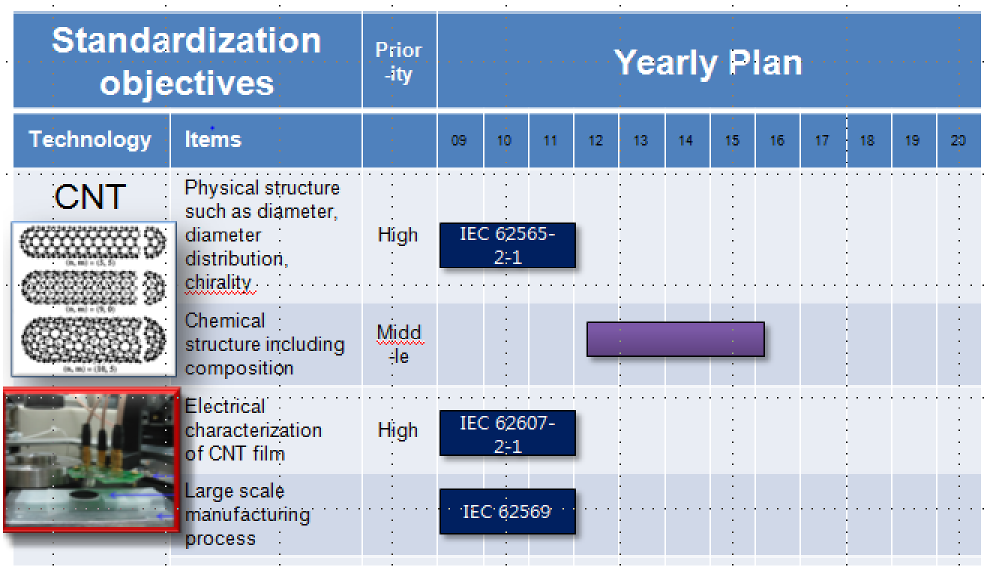
In IEC TC113 a survey on nano-electrotechnical standardization needs was initiated by the National Institute of Standards and Technology (NIST) in the USA to establish a strategy of standardization priorities regarding the nanoelectronics area. A TC 113 Project Team was then organized to build a “Nanoelectronics standards roadmap”. This document covers nanoscale devices and nanomaterials which will be in the market or are already commercialized for nanoelectronic applications. When selecting the devices and materials to be included in the roadmap, the Project Team considered their market size and the period of time needed for their technology development. Because most of the experts in TC 113 are from an electronics background, the first version (Part A) of this roadmap covers electronics and ICT (information and communication technology) rather than energy or convergence technologies.

Regarding nanomaterials, roadmaps for carbon nanotubes (CNT), graphene, nanofibres, nanoparticles and quantum dots were established. For each material there are several detailed items that need to be standardized, including physical properties and characterization methods. Some of such standards are already under development in TC 113, such as IEC 62565-2-1 and IEC 62569.

In the nanoelectronics device roadmap, nanoscale contacts, CNT interconnects, three-dimensional nanotransistors, nanoscale memory devices, and molecular devices were selected. Though the priority was on memory devices and new types of transistors, molecular devices were included in this version considering the impact of this technology.

The time span of the roadmap is important in order to cover the technology which may be realized in a certain period of time. However, with regard to nanoelectronics development, little information on the average technology development period is available at this stage. Thus TC 113 set the span of the roadmap up until the year 2020 to show the starting point of standardization tasks and the end of activity.

As the format should give insights and detailed information to the user of the roadmap, the Gantt chart format was used, including photos (see Figure 1). When a new version of the roadmap is prepared, TC 113 will develop a new format in parallel, which can give more accurate information to users.



Standardization objectives		Priority	Yearly Plan											
Technology	Items		09	10	11	12	13	14	15	16	17	18	19	20
CNT	Physical structure such as diameter, diameter distribution, chirality	High	IEC 62565-2:1											
	Chemical structure including composition	Middle				▨	▨	▨	▨					
	Electrical characterization of CNT film	High	IEC 62607-2:1											
	Large scale manufacturing process		IEC 62569											

IEC 2281/13

Figure 1 – Roadmap format

IEC NANOELECTRONICS STANDARDIZATION ROADMAP

1 Scope

This Technical Report covers nanomaterials and nanoscale devices. To achieve consensus more quickly when building the roadmap, an ICT "More Moore" area has been adopted for the priority standardization items of this first version, as shown in Table 1.

Table 1 – Categories and detail potential products

Categories		Detail potential products	Version 1
Nanomaterials	Zero-dimensional nanomaterial	Nanoparticles/Nanopowders Quantum dot	√ √
	One-dimensional nanomaterial	Carbon nanotube Nanowire (Ⅲ-Ⅴ, Ⅱ-Ⅵ, ZnO)	√
	Two-dimensional nanomaterial	Nanofunctional thin film Nanostructural film Graphene	 √
	Three-dimensional nanomaterial	Nanopore materials Nanocomposites	
Nanoscale devices	Nanoelectronic devices	Nanoscale non-volatile memory devices 1- and 3-dimensional nanoscale transistors Single electron transistor Nanoscale logic devices Nanoscale interconnection Post-CMOS signal processing	√ √ √ √
	Nanoscale optical devices	Silicon optical devices Photonic crystal optical devices All-optical logic devices Quantum dot optical devices	
	Nanoscale magnetic devices	Highly integrated memory devices High-speed magnetic logic devices	√ √
	Molecular devices	Molecular logic device Molecular memory device Molecular sensors Molecular mechanics devices Molecular optical devices	√ √
	Nanomaterials-based flexible devices	Nanomaterials-based flexible devices Nanomaterials-based displays	
Nanofabrication processes, equipment measurement	Nanofabrication process	Nano lithography Self-assembly	
	Nanoscale metrology and simulation	SPM	

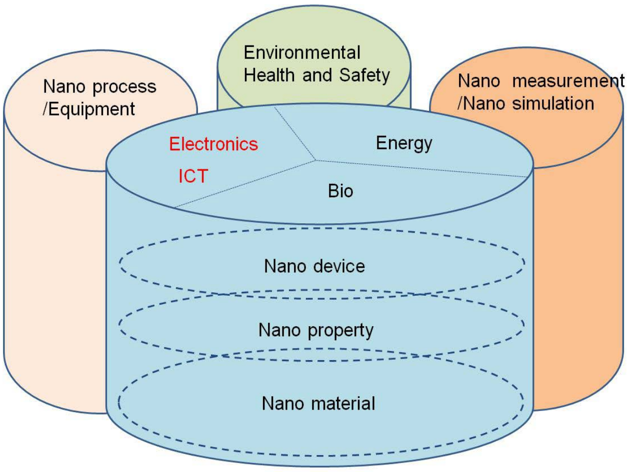
2 Background

2.1 General

The development of an "IEC nanoelectronics standardization roadmap" is necessary to establish a common standardization strategy in the area of nano-electrotechnology. The first step for determining standardization needs was carried out through a survey conducted by the National Institute of Standards and Technology (NIST) in the USA. The goal of this survey was to begin building a consensus among members of the nano-electrotechnology community on a framework leading to inputs for consideration in standards development. The results from the survey were reported in 2009. [1][1]

Nevertheless, a standardization roadmap requires more than a framework of priority needs for standards established by the foregoing survey results. It requires a vision from technical experts as to which products will be developed in the future and which technologies will be available to realize them. That means a vision of market needs and technology availability.

Figure 2 shows technologies and their related markets. It will be possible to make the roadmap for all technology areas, such as electronics, information and communications technology (ICT), bio, energy etc.. In this version, we focus on the existing information available to develop a roadmap, for example the area of "More Moore", including nanotechnologies and nanomaterials, which makes it possible to achieve technology innovation in terms of integrity and high performance. The areas not covered by this document will be provided separately after considering demands for standardization.



IEC 2282/13

Figure 2 – Technologies and related products

The interaction between technology, product and the standardization roadmap is illustrated in Figure 3. Most of the stakeholders in nanotechnology have their own roadmap, and from time to time, publicly available roadmaps are under development. The problem here is that company-owned roadmaps are not available to the IEC and there is no guarantee that publicly available roadmaps they will be actualized on a regular basis. Therefore, IEC TC 113 decided to develop its own integrated roadmap based on its view of technologies, products and standards.

From an IEC strategic point of view, such a project could have some very important advantages. Assuming that the roadmap would be structured in line with the IEC technical committee structure, it would provide an effective planning tool for the IEC as a whole. It would support the work of IEC TC 113 by providing the relevant market information to establish and review its programme of work. If the IEC owns the product/technology/standards roadmap and the roadmap update process, it can be used in areas of interest other than the

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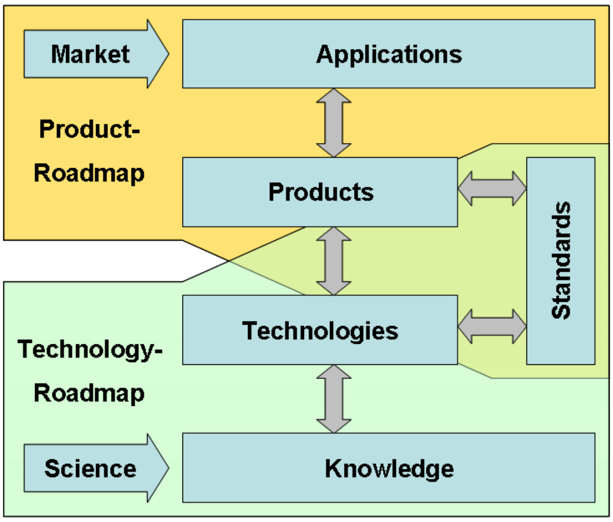
[1] Numbers in square brackets refer to the Bibliography.

production of standards. Last but not least, the roadmap would demonstrate that the IEC has a position in nanotechnology which is agreed among relevant industry stakeholders.



IEC 2283/13

Figure 3 – Interaction of product, technology and standardization roadmaps

2.2 Classification of nanotechnology

2.2.1 General

The nanotechnology industry can be largely divided into nanomaterials, nanoscale devices, nano-biotechnology, the nanofabrication process, equipment and measurement areas.

2.2.2 Nanomaterials

These are materials that control, combine, and mix materials at the nanoscale to remarkably improve physical properties and to create new physical properties and functions. They apply to mechanics, energy, environment and IT-related systems.

2.2.3 Nanoscale devices

These are devices that can perform special functions using unique characteristics of nanoscale materials.

2.2.4 Nano-biotechnology

This is an area of science and technology operating, analysing and controlling a system combining biosystems with nanomaterials and/or nanoscale devices.

2.2.5 Nanofabrication process – Equipment – Measurement

This is manufacturing technology of nanoscale processes (under 100 nm) that form nanoscale parts and devices, as well as equipment technology and performance measuring of nanomaterials, devices, subsystems and systems.

3 Current status and prospects

3.1 Related markets

Currently, zero-dimensional nanopowders, TiO_2 nanopowders for photocatalyst and anti-bacterial silver nanoparticles are widely commercially available materials. The market size of TiO_2 nanopowders for photocatalyst is 10 million US dollars (2005) worldwide.

The tool market is the largest area of application and the market of nanostructure thin film materials internationally. Although it is difficult to forecast the status of world tool markets, the world market of diamond cutting tools is estimated to be about 13 billion US dollars based on information from 1999.

The largest part of the market of mass production equipment is in nanostructure thin film materials, as well as tools, moulds and various mechanic parts. At present, equipment companies operating worlwdie (e.g. Kobe, Cemecon, Balzers, Huazer[2]) have developed their equipment and handled materials, processes and patents collectively.

The market of nanocomposite materials is led by polymer matrix nanocomposites, with a world market size of about 5 billion – 7 billion US dollars in 2009. The market of ceramic nanocomposite materials was about 2,5 billion US dollars after 2010.

The market has shown a consistent growth trend due to continuous growth in several ten gigabyte (GB) high capacity flash memory and DRAM components. Given the vague overlapping area of existing semiconductor and nanotechnology markets, it is important to analyse characteristics, to standardize the modelling and design methodology and to obtain circuit IP based on nanoelectronic devices to address the nanotechnology market.

III-V compound semiconductors including nitride-based nanostructures will be used for light-emitting diodes (LEDs), and their scope of application continues to expand, including portable appliances, LCD (liquid chrystal display) backlight, automobile lighting.

The most active area is the LED market, and many players are striving to launch into the general lighting market. The LED lighting industry is expected to replace almost all lighting areas such as traffic signals, construction and automobiles as well as LCD backlighting and general lighting. In addition, development and commercialization of quantum dot light receiving devices and infrared devices are expected to bring about a revolution in the area of image sensors. Solar energy is an area that has seen double-digit growth rates due to worldwide energy issues.

The flexible electronic device market is expected to grow rapidly from 16 million US dollars seen in 2008 to 1,314 million US dollars in 2013. The market is expected to be led by small and medium applications focusing on new mobile phones.

Since the world market of ITO (indium tin oxide) transparent electrode thin films for 2006 was 592 million US dollars, and that of touch panel, EL (electroluminescent) backlight and transparent conductivity films for 2006 was 90 million US dollars, the percentage share of transparent conductive electrode films was about 0,96% of flat panel display industry revenues in 2006.

The market for flexible transparent electrodes is expected to grow up to 1,929 million US dollars in 2015 for the display market, and it is expected that it may be applied to electrode materials for RFID (radio-frequency identification) and for solar cells.

3.2 Technology development directions for nanomaterials

3.2.1 General

Improving efficiency is important when developing a photocatalyst by doping of various metal oxides, high density coating films and by controlling particle size in the case of zero-dimensional nanomaterials.

For silver nanopowder, the control of silver nanoparticle size in the matrices is important when used for sterilization and anti-bacterial purposes.

Nanowires are used for transistors, sensors and other applications such as field emission display and NEMS (nanoelectromechanical systems).

The industrialization of nanomaterials is expected in optoelectronic devices and biotechnology areas.

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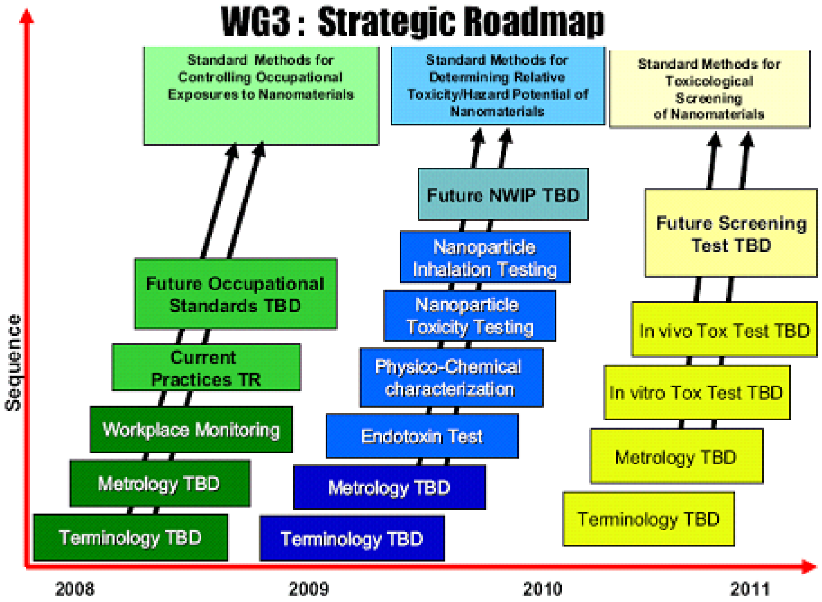
[2] When companies are referenced specifically in this technical report, this information is given for the convenience of users of this document and does not constitute an endorsement by IEC.

In ISO TC 229, toxicity of nanomaterials is addressed and a roadmap is in place for controlling occupational exposures to nanomaterials, toxicity and the hazard potential of nanomaterials, and for toxicological screening of nanomaterials (See Figure 4).



IEC 2284/13

Figure 4 – ISO 229 WG3 roadmap for standardization of nanomaterials: www.nanosafe.org

3.2.2 World leading group status

In Japan, 50 nm size particles were developed as standard materials in 2005, and 100 nm size particles were developed in the atmospheric environment.

Matsushita has developed II-VI semiconductor quantum dots. Studies on ZnO quantum dots and nanorods are also active in Japan, China and the USA.

In the case of nanowire technology, electronic materials development is active, such as p-n junction formation in nanowires or using nanowires as a conduction channel to build field effect transistors.

The application of nanowires is moving to the area of energy conversion.

An active attempt has been made to apply nanowires to bio and medical areas.

Doping of nanowires and configuring of heterostructures are still problematical.

Nanostructured thin film materials of metal-nitride are known to have superior hardness and wear-resistance features when compared to traditional materials.

Nanostructured thin film materials that have attracted recent attention can be classified into nanocomposite structured thin film materials and multiple structure thin film materials.

In the 1980s, Holleck of Germany and Helmersson of Sweden independently developed nanostructured thin film materials. After this, Barnett group of Northwestern University worked on superlattice nanoscale multiple layer thin films. They registered a patent for equipment and process (US Patent No. 5,783,295). Munz group of Sheffield Hallam University got commercially applicable results. Sumitomo has developed nanoscale multiple layer structure thin film, and registered related patents (US Patent No. 5,503,912).

Nanoparticles with a surrounding amorphous layer are reported to have excellent hardness matching that of diamond, as well as wear-resistant features and high temperature oxidation resistance. They maintain a stable structure at high temperature, different from nanoscale multiple layer structure films.

3.2.3 Nanopore materials

Development of nanopore adsorbent agents with specific use for each industry is active and commercialization has begun. In the area of energy, high-efficiency process utilizing nano porosity is important.

Research and development of nanopore materials for separation of degree of processing of infinitesimal noxious material are in progress, with hydrogen and electric energy efficiency being the core focus.

3.2.4 Nanocomposite materials

Technology development of nanocomposite materials in the USA is conducted in the “Nanostructured material by design" program of the National Nanotechnology Initiate (NNI) announced in 2000. The U.S. Department of Defense is devoted to the development of high strength-to-weight materials, the Department of Energy, to the development of wear-resistant and corrosion-resistant ceramic nanocomposite materials, and NASA, devoted to the development of nanocomposite materials with high strength and low specific gravity (light weight) for space shuttles.

National Aeronautics and Space Administration (NASA) has developed ultra-light carbon nanocomposite materials with high heat resistance to replace body parts. These were manufactured with existing carbon textile and fiberglass for improved heat resistance performance and fuel savings for space shuttles. NASA attempted to dominate the world market in the area of new concept aerospace technology to be expanded in the future.

In Japan, NEDO (New Energy and Industrial Technology Development Organization) initiated a joint project government-industry-university for nanocomposite material development. METI allocated a 400 million Yen budget in 2003. Together with development of nanocomposite material technology, nanocomposite materials such as nano metal powder, carbon nanotube and nano textiles are actively produced by companies including Mitsui Corporation.

3.3 Overall technology status and prospects of nanoelectronic devices

PCRAM, ReRAM and polymer RAM are under development for the next-generation non-volatile or high-performance memory that will replace existing floating gate type NAND flash memory.

Reduction of traditional gate oxide based on SiO_2 has reached its limit and high-k dielectric materials are under investigation. Material, structural or design methods are available.

In terms of material and process technology trends, parasitic components such as source/drain resistance of transistor, parasitic capacitance, contact resistance, low dielectric material and metal bus lines are becoming important. Process or optimization techniques that can solve problems, rather than materials themselves are becoming more important. Several processes (dry etching, wet cleaning, photo-lithography, CVD, design technology, etc.) together offer solutions.

Nanotube electronic materials are specialized applications and widely studied in the area of bio and environment sensors.

New electronic materials phenomena using semiconductor nanowires such as silicon or ZnO have been announced. Along with this, specialized applications, for example, integrated technology applying to flexible electronic materials, have evolved.

In the area of three-dimensional nanoscale transistor technology, various cases of applications have been reported. The results apply to bulk FinFET structures and PiFET(partially-insulated FET) to DRAM cell transistor and SONOS flash memory cell transistors.

Development of GAA (gate-all-around) structures are at a basic level. Sufficient understanding and modelling of quantum mechanical effects and ballistic transport have not been accomplished.

Three-dimensional transistors have been applied on a limited basis to memory cells, which have a high level of integration and repeated structures. To pursue a better performance of overall circuits, the degree of design freedom and AC characteristics are expected to be important for industrialization.

Development of hybrid circuits for single electronic transistor and CMOS devices is in progress, but there are technical problems to overcome including process compatibility and room temperature operation.

Systematic research on variability among devices and parasitic electric charge is needed, and the importance of related research is expected to be important in the future.

At present, logic nanoscale devices have diverse possibility as three-dimensional transistors, single electronic transistors, nanowire transistors and new material-based transistors.

Nanoscale device logic is likely to vary by application area (super-high frequency, super-low power, very large scale integration (VLSI), and super-minute signals). Effective research and development resource allocation will follow the establishment of key control characteristics for nanoscale device logic.

Three-dimensional transistor related technology such as high-k dielectric oxide, metal gate, tri-gate, channel of III-V material and optical wiring techniques should be monitored. In the case of research groups where IBM has been active, SOI technique, channel stress technique, metal electrode technique and air-gap metal bus lines are worth noting.

Nanotube electronic materials are developed as specialized applications for bio sensors and environment sensors, and some companies have launched practical products onto the market.

Reliability and key control characteristics are expected to be important for the commercialization of the technology.

The three-dimensional nanoscale transistor is expected to be brought out, beyond the fixed concept of planar semiconductors. Important areas for the success of this technology will be physical-IP, reliability, characterization methods and circuit lifetime.

Considerable research has been done to address the problems of parasitic charge variability among devices.

While analysis of parameters related to DC, AC and RF has been done to some degree, key control characteristics from the general aspect of CMOS circuitry are critical and the key control characteristics which can reflect the phenomenon that occurs in a nanoscale device are still weak.

Standardization and the differentiation by nanoscale device key control characteristics according to applications such as super high frequency, super low power consumption and ultra large-scale integration (ULSI) is expected.

Artificial neural networks, neuromorphic architectures, crossNET and spintronics are under development in the USA, and will be diversely connected with CMOS technology. Considerable progress has been made on basic modelling and simulation on this technology merging.

4 Nanomaterials technology, scenario and standardization roadmap

4.1 Technology

4.1.1 Classification of nanomaterials

This standardization roadmap covers nanomaterials with a size of elements less than 100 nm or technology utilizing specific physical properties of materials at the nanoscale. Nanoparticles, quantum dots, nanowires, carbon nanotubes (CNT), nanostructured thin films, nanopore materials and nanocomposite materials are included. Standardization of nanomaterial technology deals with manufacturing methods, standard material development and the development of protocols for key control characteristic measurements.

Table 2 – Classification of nanomaterials

Classification	Detailed nanomaterials
Zero-dimensional nanomaterial	– Nanoparticle (or nanopowder) [a]
	– Quantum dot
One-dimensional nanomaterial	– Carbon nanotube (CNT)
	– Nanowire
Two-dimensional nanomaterial	– Nanostructure (and functional) thin films
	– Graphene
Three-dimensional nanomaterial	– Nanocomposite material
	– Nanopore material

[a] From the physical and measurement aspect, these can be classified as three-dimensional nanomaterials, but are classified as zero-dimensional materials here in consideration of similarity of standardization items in this classification of standardization targets.

4.1.2 Standardization items of zero dimensional nanomaterials

4.1.2.1 Nanoparticle (or nanopowder)

For one dimensional materials that have less than 100 nm size of polymer, organic, metal, oxide and non-dioxide (chalcogenide, nitride) particles, standardization for manufacturing methods, development of reference materials and physical property measurement protocols are needed.

Table 3 – Characteristics to be considered in developing standards for nanoparticles

Physical characteristics	Other characteristics
Diameter and size distribution Shape Density Surface area Chemical structure Crystal structure Determination of nature and concentration of contaminants Dispersability Purity Electrical properties Magnetic properties Optical properties Thermal properties Structure and shape of polymeric and organic agglomerates	Handling safety Exposure assessment to ambient air Safe disposal including destruction Exposure assessment to water Explosion potential Whole life cycle analysis Toxicity of contaminants

4.1.2.2 Quantum dots

Nanoscale metal, oxide, and non-oxide (chalgognide, nitride) particles with quantum phenomenon need standardization in the areas of manufacturing methods and physical property measurement protocols.

Table 4 – Characteristics to be considered in developing standards for quantum dot

Physical characteristics	Other characteristics
Diameter and height Size distribution Chemical structure Ordering Determination of nature and concentration of contaminants Density of quantum dot Electrical properties Magnetic properties Optical properties Thermal properties	Handling safety Exposure assessment to ambient air Disposal safety Exposure assessment to water Explosion potential Whole life cycle analysis Toxicity of contaminants

4.1.3 Standardization items of one-dimensional nanomaterials

4.1.3.1 Carbon nanotubes (CNT)

For carbon nanotubes with single or multiple wall structures, development of physical property measurement protocols is in progress.

Table 5 – Characteristics to be considered in developing standards for CNT

Physical characteristics	Other characteristics
Diameter distribution Length distribution Chemical structure Determination of nature and concentration of contaminants Dispersability Dechanical properties Degree of functionalization Bond strength with matrix Purity Terminology Chirality Toxicity of contaminants Electrical properties Magnetic properties Optical properties Thermal properties Structure and shape of agglomerates	Handling safety Exposure assessment to ambient air Disposal safety Exposure assessment to water Explosion potential Whole life cycle analysis

4.1.3.2 Nanowires

For nanowires less than 100 nm in diameter with an aspect ratio over 10, development of physical property measurement protocols is needed.

Table 6 – Characteristics to be considered in developing standards for nanowires

Physical characteristics	Other characteristics
Diameter distribution Length distribution Chemical structure Determination of nature and concentration of contaminants Dispersability Mechanical properties Degree of functionalization Bond strength with matrix Purity Terminology Chirality Toxicity of contaminants Electrical properties Magnetic properties Optical properties Thermal properties Structure and shape of agglomerates	Handling safety Exposure assessment to ambient air Disposal safety Exposure assessment to water Explosion potential Whole life cycle analysis

4.1.4 Standardization items of two-dimensional nanomaterials

4.1.4.1 Nanostructured thin film

Standardization of mechanical properties for nanostructure thin film materials covers the layer thickness range of less than 10 μm but with various surface shapes.

Table 7 – Characteristics to be considered in developing standards for nanostructured thin film

Physical characteristics	Other characteristics
Layer thickness Interface position Grain size Diameter distribution Surface roughness distribution Surface area Chemical composition Hardness Elastic modulus Toughness Friction coefficient Wear-resistant feature Bond strength with matrix Oxidation resistance	