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TECHNICAL REPORT

colour inside

IEC nanoelectronics standardization roadmap

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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- withdrawn,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

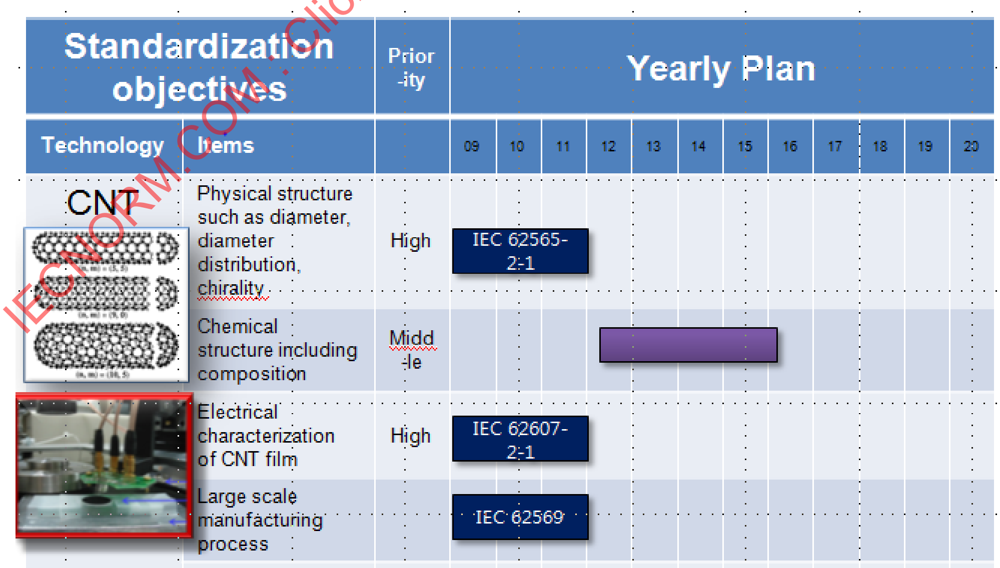
In IEC TC113 a survey on nano-electrotechnical standardization needs was initiated by the National Institute of Standards and Technology (NIST) in the USA to establish a strategy of standardization priorities regarding the nanoelectronics area. A TC 113 Project Team was then organized to build a “Nanoelectronics 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.



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.

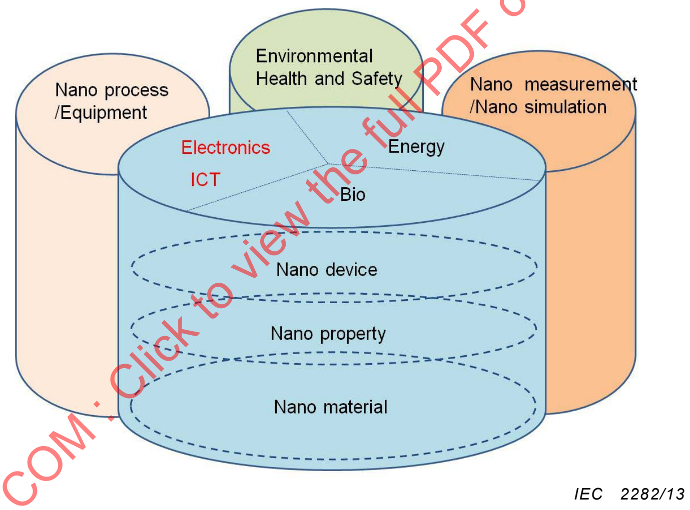


Figure 2 – Technologies and related products

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

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.

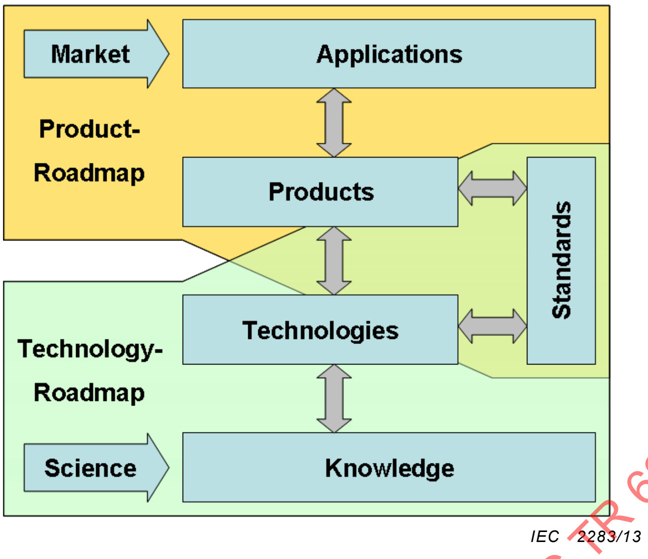


Figure 3 – Interaction of product, technology and standardization roadmaps

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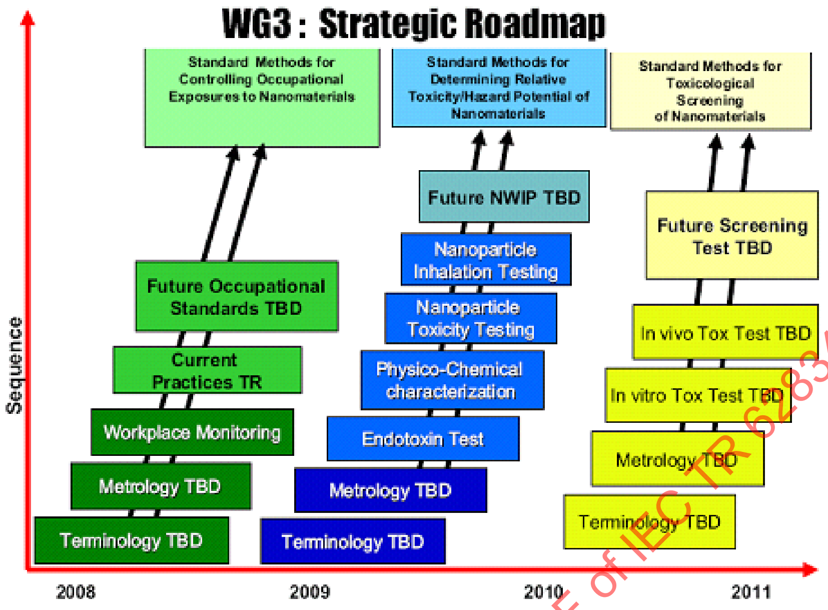
2 When companies are referenced specifically in this technical report, this information is given for the convenience of users of this document and does not constitute an endorsement by IEC.

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

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	Handling safety
Length distribution	Exposure assessment to ambient air
Chemical structure	Disposal safety
Determination of nature and concentration of contaminants	Exposure assessment to water
Dispersability	Explosion potential
Dechanical properties	Whole life cycle analysis
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	

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	Handling safety
Length distribution	Exposure assessment to ambient air
Chemical structure	Disposal safety
Determination of nature and concentration of contaminants	Exposure assessment to water
Dispersability	Explosion potential
Mechanical properties	Whole life cycle analysis
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	

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	

4.1.4.2 Graphene

Table 8 – Characteristics to be considered in developing standards for nanostructured thin films

Physical characteristics	Other characteristics
Impurity Layer number 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	

4.1.5 Standardization items of three-dimensional nanomaterial

4.1.5.1 Nanopores

The materials composed of micropores (less than 2 um) and mesopores (2 nm – 50 nm) are defined in IUPAC, including manufacturing method, development of standard materials and physical property measurement protocol.

Table 9 – Characteristics to be considered in developing standards for nanopores

Physical characteristics	Other characteristics
Specific surface Pore volume Pore size distribution Structure and shape of pores Density Electrical properties Magnetic properties Optical properties Thermal properties Fluid diffusion rate Gas adsorption/desorption properties Liquid adsorption/desorption properties Molecular sieving effect	

4.1.5.2 Nanocomposite Materials

These are materials such as nanopowders or nanoparticles having a diameter less than 100 nm in the metal, oxide, non-oxide and polymer matrix. Any carbon nanotube dispersed matrix is included in this category.

Table 10 – Characteristics to be considered in developing standards for nanocomposite materials

Physical characteristics	Other characteristics
Diameter and size distribution Shape Density Interfacial strength Dispersability Mechanical property-strength Mechanical property-toughness Mechanical property-hardness Mechanical property-wear resistance Electrical properties Magnetic properties Optical properties Thermal properties hemical properties-anti virus	

4.2 Scenarios

4.2.1 Scenario for nanoparticles (or nanopowders)

Many universities and research institutes have developed relevant technology for 0 dimensional nanomaterials. Size of nanoparticles and distribution control are the main issues of development.

Initially, TiO_2 nanopowders have been commercialized in cosmetics and paints. With Au or Ag nanopowders are mixed at various percentages, which implement various colours in cosmetics.

Research on medical application of magnetic nanoparticles for imaging diagnosis of nano-bio is in progress.

It is important to develop nanoparticle dispersion control techniques to solve the problems of nanoparticle-related applications.

The areas of application of nanoparticles are solar cells, photocatalysts, electrochemical materials of fuel cell anodes.

Composite nanoparticles such as amphiphilic polymer nanoparticles and amphiphilic inorganic nanoparticles are used in environmental pollution treatment (water processing, soil washing, air purification, etc.).

Standardization on measurements, definition or material features such as specific surface area, distribution and size of nanoparticles are needed to expand the industrial application of nanoparticles or nanopowders. Currently commercialized products are Ag and TiO_2.

Nanoparticles or powders have a particle size distribution which is dependent the on types and amounts of amphiphilic polymer or amphiphilic organic materials used during the process. Accordingly, it is required to standardize such amphiphilic polymer or amphiphilic organic materials along with standardization of nanopowder and particles.

4.2.2 Scenario for quantum dots

It has been established that nanoparticles become extremely small to several ten nanometres.

While research on quantum dots has been primarily directed toward compound semiconductors and silicon, research on metal and oxide quantum dots is now under development.

In the case of Si and compound semiconductors, manufacture is conducted through various methods such as PECVD, pulsed laser CVD, MBE and MOCVD. II-VI semiconductor quantum dot development is active and used on laser and optical devices.

Metal oxides are formed by various methods such as sol-gel, thermal spray, hydrothermal, electrochemistry or gas evaporation. Due to the lack of nanoparticle dispersion control and particle size variation control techniques, they are not yet suitable for optical or electronic applications.

To enhance LD, LED applications, it is necessary to standardize on measurement methods for nanoparticle specific surface area, distribution and size.

4.2.3 Scenario for carbon nanotubes

Predominant applications for CNTs include composite reinforcement (nanotube reinforcement composite), energy storage (hydrogen storage), energy (cathode electrode of battery) and bio-sensors. Large area appliances for display devices are FED.

While CNT production has matured enough to allow mass production, it has not yet reached to the level that single/multiple wall construction or chirality can be controlled.

It is expected that development of bulk unit from the powder type will become more prevalent than the use of the features of single CNT.

CNT’s are expected to be heavily utilized in the areas of energy, catalysts, environment and structure. Integrated technology will be studied mainly in the electrical and electronic areas.

Among various applications of CNT, LCD BLU (back light unit) applications and transparent electrodes are expected to be industrialized soon:

– LCD CNT BLU technology: Several companies including Samsung obtained large-area display BLU technology. It is important for commercialization whether or not large area process technology can be available in the near future.
– CNT transparent electrodes: Highly conductive electrode manufacturing technology is being developed, focusing on polymer dispersion composite or CNT filtering-transfer technology.

In industry, standardization of scope, feature and definition of size, distribution and specific surface area of CNT should be pursued, targeting BLU and transparent electrodes, which can be industrialized.

It is essential to fabricate CNT bundles for nanoelectronics applications. The high conductivity and high current carrying capacity of CNT bundles can be used in vias, contact plugs, and lateral interconnects of LSIs. They can also be used in interconnects of flexible and printed electronic devices.

The conductivity of CNT bundles is strongly dependent on the density of CNTs. However, there is a lack of information on the densities of CNTs provided due to the absence of a standard technique for this measurement.

A test method should be considered for measuring the density of CNTs. Typically, there are two methods generally followed; (i) SEM (scanning electron microscopy) observation measurement, and (ii) TEM(transmission electron microscopy) observation measurement.

Moreover, the conductivity of the individual CNTs in CNT bundles is strongly dependent on CNT growth conditions. However, there is a lack of information on the conductivity of individual CNTs due to absence of a standard technique for this measurement.

A test method should be considered for measuring conductivity of individual CNTs. There are typically two methods generally used: (i) 4-probe measurement, and (ii) 4-point probe measurement. Since the properties of CNT bundles are limited by the damage occurring during measurement, the test methods including the fabrication process of contact electrodes should be clearly defined.

Standard(s) related to these measurements will enable manufacturers to provide suitable information for developing novel materials including CNTs for use in nanoelectronics.

4.2.4 Scenario for nanowires

Based on results of technology development and evaluation of the features and composition of various nanowires, technology development is in progress for areas such as sensors, which do not require precise integration from the possibility of electronic materials composition.

Technology development is in progress for nanowire composition using CVD and wet chemical methods. While there are various compositions and variations of nanowires, mass production technology has not yet been achieved.

Application technology is intensively developed in the area where low integrity devices can be applied. Sensors and optical devices are being actively researched.

For nanowire optoelectronic device technology, high photoelectric efficiency has been implemented in research centres focusing on GaN nanowires. Development of future technology for large-area device composition is in progress.

Concerning nanowire sensor technology, chemical material detection technology using single nanowires has been achieved. Research continues for technology for multiple integration structures.

Standardization of size, distribution and specific surface area of nanowires will be directed toward sensor and optoelectronic devices, which can be industrialized within relatively short period of time.

In the case of nanowire optoelectronic device technology, standardization of size, distribution, specific surface area, composition and structure measurement technologies of nanowire are first priorities. Standards for nanowire optoelectronic characterization will follow.

4.2.5 Scenario for nanostructured thin films

Structural thin-film materials with thickness less than 10μm have high wear resistance and hardness, because their basic material is coated on the surface for improvement of function, service life and protection of bas materials.

In the case of nano multiple layer structure of thin films, materials deposited have several μm thicknesses after repeatedly depositing different thin layers with thickness of several nanometres (nm) and nanocomposite structures. They are reported to show excellent physical properties compared to existing thick film materials, including hardness, wear resistance and high temperature stability.

Given these excellent mechanical properties, nanostructured thin film materials can be applied in applications requiring wear resistance features such as coating tools, a market that is currently over 60 billion won. Thin films have also been developed for complicated applications requiring low friction and wear resistance, including automobile parts and moulds, the markets of which have been gradually expanding.

Nanoscale multiple-layer structured thin films are important because the physical properties of the film vary substantially. Industrialization of this material can be achieved when the control of nanoscale multiple-layered structures and the standardization of characterization methods are achieved.

Since the deposition process for nanostructured multiple-layer thin films can be applied to existing mass production equipment, it can be applied in existing industries where structural coating materials are used.

The most promising areas are expected to be coating cutting tools, which has an estimated market size of 60 billion won, as well as mould coating material and automobile part coating materials, the markets of which are expected to expand.

Changes in nanostructured thin film properties (wear resistance, hardness, toughness, oxidation resistance) due to structural difference (layer thickness in nano multiple layer structure, fraction of ground boundary phase of particle size in nanocomposite structure) are severe. Accordingly, standardization on the structure showing the optimal features for each application based on analysis technology is urgent. Performance improvements and accurate service lifetime estimates can be achieved in the area of application from the feature and structure of materials itself, only when the standardization of nano thin film materials is established.

4.2.6 Scenario for sheet resistance characterization of CNT films

The fabrication of CNT films is essential for nanoelectronics applications. The unique conductivity of CNT films can be used in field-emission displays (FEDs), flexible displays, or printed electronics.

According to many results obtained so far, the conductivity of CNT composite films is strongly dependent on the conductivity of the CNT itself. However, there is a lack of information on the conductivities of CNT products provided by suppliers due to absence of a standard technique for this measurement.

CNT sampling is a key issue to measuring its conductivity, one of its intrinsic properties, in order to establish the standard method. There are several parameters in preparing a homogeneous CNT film in terms of dispersability and thickness. The controlling parameters are the type of solvent, the CNT dose, temperature, etc.

A standard test method should be considered. There are two typical methods generally used in measuring the conductivity of a film-type sample as follows:

a) 4-probe measurement, and
b) 4-point probe measurement.

Since the physical properties of CNT films are limited in size and mechanical strength, the interval of each probe, the current applied to the sample, the pressure to the sample applied by the probes and etch should be clearly defined.

Standards related to this measurement will enable manufacturers to provide suitable information for developing novel materials including CNTs that can be used in nanoelectronics.

4.2.7 Scenario for wear resistance and exposure test of CNT films

CNT film is a film-like structure composed of CNTs and polymeric resin. The CNTs can be single walled or multi-walled depending on the required characteristics of a product. CNT film can be deposited on various substrates such as polymer, glass, fabrics, etc. The deposition is accomplished through conventional coating technologies including spray or roll coating.

CNT films are used as a basic component in various applications such as transparent conductors, flexible electronic devices, heaters, protection from electrostatic discharge, etc. The thermal, electrical, and mechanical properties of CNT films are very important for the successful commercialization of such applications. For example, CNT film used in flexible electronic devices must have low sheet resistance together with high elongation during stretching or bending of the electronic devices.

One of the critical issues related to CNT films is toxicity of CNT. The geometry of CNT is very similar to asbestos, and many researchers worry about the influence of CNT to human health and the environment. The toxicity of CNT is still under debate, and could depend on their synthesis method, aspect ratio, and dimensions. Some organizations wish to restrict the use of CNT until their safety is assured.

CNTs in CNT film can be exposed to external environment due to wear or fracture of the film. Products made of CNT film usually experience mechanical and thermal load during their lifecycle. The mechanical and thermal load can lead to delamination, fracture, wear, and fatigue of the CNT film and customers can be unintentionally exposed to CNTs. To prevent this exposure, it is necessary to determine the failure modes of CNT film or CNT-based products, and to evaluate the exposed quantity of CNT during the product's service life. It is essential that the amount of exposed CNT be much less than established exposure limits based on toxicity data.

For this purpose, it is necessary to develop standard test methods for mechanical failure of CNT films together with testing methods for electrical and thermal behaviours. The thickness of CNT film is usually less than 1 μm and existing standards for metal and polymer are not applicable.

One of the key components in the test standard should be the evaluation of the exposed quantity of CNT, where the quantity of the exposed CNT is correlated with the mechanical damage in the CNT film.

4.2.8 Scenario for thermal characterization of CNT films

Since CNTs are very slender and have high electrical conductivity, networks of CNTs become an electrically conductive film.

Many efforts to use conductive CNT films as a film heater have been reported. In the near future, the CNT film heater will replace the metallic heating wire in various applications due to the uniform heating capability, simple fabrication process and low material price.

For industrial use of CNT film heaters, understanding and precise measurement of their thermal behaviour are very important. In the course of commercialization, an international standard evaluation method will be essential.

It is well known that CNTs have extremely high thermal conductivity. Hence, CNT films could be used as a thermal management device in the future. In this context, standardization of thermal property measurements will be important from an industrial viewpoint.

4.2.9 Scenario for graphene

Graphene is a monolayer of carbon atoms hexagonally bonded via sp^2. Its π-conjugated network donates peculiar conductivity to this carbon allotrope. Due to high potentiality in many applications to industries such as CNTs, the same methodology applied to CNT standardization can be adopted.

ISO TC 229/IEC TC 113 JWG2 developed a matrix table for single-wall carbon nanotubes (SWCNT) whose rows represents properties to be standardized and whose columns represents techniques to be used for standardization. Each element in the matrix table represents a potential standardization item.

Since CNT is defined as a roll of graphene, there is a similarity between standardization of graphene and that of SWCNT. However, there is a critical difference in their geometry. Graphene is two-dimensional nanomaterial while SWCNT is a one-dimensional nanomaterial. The matrix for graphene standardization is designed with consideration to both the similarities and differences between the two nanomaterials, and is presented in Table 11.

Table 11 – Matrix for graphene characterization

		TEM	SEM	AFM	XPS	Raman	UV-Vis-NIR	TGA	Ellipsometry	4-probe
Morphology	Roughness		Possible	Yes					Possible	
	Thickness			Yes					Yes	
	Carbon array	Yes		Yes	sp^2 or sp^3					
Purity		Yes	Carbon and noncarbon			sp^2 or sp^3		Noncarbon contents		
Dispersability/ solubility		Partly	Partly	Partly			Yes			
Transmittance							Yes			
Young's modulus				Possible						
conductivity	Electrical			Possible		Yes				Yes
	Thermal									

Other methods, not listed in the above matrix, should be considered.

The standards related to this measurement enable manufacturers to provide suitable information for developing this frontier material, which can be used in nanoelectronics related to the display and semiconductor industries.

In order to accelerate standardization activities, work with other groups such as ISO TC 201, ISO TC 202, VAMAS TWA2, VAMAS TWA29, etc. is recommended.

4.2.10 Scenario for nanopores

Activated carbon is the most representative example of nanopore material and is used in various areas due to its excellent absorption capability. Inorganic oxides including silica and alumina are the base materials for nanopore formation.

Various types of fabricated zeolite as well as natural zeolite are well known nanopore materials.

Mesoporous materials of 2 nm - 10 nm can be fabricated, and metal-organic frameworks (MOF) with pores whose size is smaller than zeolite by several nm can be designed and composed. This technology will expand the scope of applications of nanopore materials.

Nanopore materials are utilized in various areas including energy and environment as well as chemical engineering of separation processes. Their application in the field of batteries, fuel cell, super-capacitor and hydrogen storage is expected. It is also expected that nanopore materials will be actively used as solutions to environmental issues such as processing of pollutants in air and liquid.

Control of the pore size for nanopore materials applications is critical.

4.2.11 Scenario for nanocomposite materials

Development of nanocomposite materials technology reinforces CNT and nanoscale particles in the polymer, metal and ceramic matrix. Composite material technology has been developed to improve electrical and mechanical features.

Polymer matrix nanocomposite materials reinforced with CNT or nano-clay or nano-silver with enhanced antibacterial and mechanical features and thermal resistance will soon be used for practical purposes.

Some products are developed from CNT dispersed functional polymer nanocomposite materials such as flexible thin films, electrostatic application polymers, coloured exterior materials to shield electromagnetic waves with high electrical conductivity. CNT dispersed composite materials are under development in order to improve optical features.

Technology for ceramic matrix nanocomposite materials has been developed in a way that enhances the toughness of materials with various types of nanoparticles. Recently, nanocomposites have been developed for ceramic matrix nanocomposite materials with complex functionality. While commercialization has been achieved in part with ceramic matrix nanocomposite materials, further development has been pursued to overcome the limit of applications and high cost of manufacturing due to the difficulties of dispersion and densification process.

With regard to nanocomposite material manufacturing technology, new dispersion and synthesis methods have been developed, but mass production technology of nanocomposite materials with uniform dispersion has not yet been obtained.

Nanocomposite materials have been commercialized initially for applications not requiring high functionality. Nanocomposite materials presently commercialized are the nano-silver dispersed polymer composite materials with excellent antibacterial features and CNT reinforced polymer panels with high strength and light weight features for automobile exteriors.

Some possible areas for commercialization in the short term include nano-clay for high strength exteriors and CNT reinforced polymers as well as nano-silver dispersed polymers for their antibacterial properties.

The interface feature control, distribution and size for optimal dispersion are required in nano-silver dispersed polymer nanocomposite materials. As with clay dispersed polymer nanocomposite materials, CNT dispersed polymers are used for heat resistance, strength and processability.

CNT dispersed polymers are the most promising application of CNT and are expected to be industrialized within 5 years.

4.3 Roadmap of standardization of nanomaterials (2009-2020)

The roadmap chart for the development of standards of nanomaterials is shown in Figure 6.

5 Nanoelectronic devices technology, scenario and standardization roadmap

5.1 Technology

5.1.1 Nanoscale non-volatile memory devices

The definition of a nanoscale non-volatile memory device is a non-volatile memory device based on nano scale phenomena.

It is expected that high performance or high capacity non-volatile memory devices will overcome the scaling limit of existing flash memory devices.

Nanoscale non-volatile memory devices should have a certain level of reliability and information retention performance.

Cell interference phenomena of high density memory devices may exist. The adjacent cells are affected by the operation of one neighbouring cell, resulting in malfunction.

5.1.2 New nanomaterial or new nanostructure for nanoelectronic devices

With the superior materials, the existing concept of Si based MOSFET can be overcome.

One-dimensional electronic materials such as nanotubes and nanowires are being actively studied for new nanostructured electronic devices.

5.1.3 Three-dimensional nanoscale transistors

Three-dimensional (3D) nanoscale devices include FinFET, multiple gate transistor (multi-gate FET), GAA (gate-all-around) FET, vertical channel transistor (vertical transistors).

3D bus suitable for 3D transistor and interconnection technology should be standardized at the same time.

5.1.4 Single electron transistors

For the single electron transistor, a solution is needed for temperature dependency of operating features, and a method of controlling neighbouring noise such as background charge.

Reproducibility is an urgent issue for this device.

5.1.5 Nanoscale logic devices

Standards for key control characteristics that can properly compare and evaluate the performances of nanoscale logic devices are needed.

Operating speed of unit devices, energy-efficiency, power consumption and on/off ratio will be the first objectives of standardization.

5.1.6 Carbon interconnects

With their large electro-migration tolerance and low electrical resistance, CNTs can be used as nanoscale wiring materials, and are thus becoming potential candidates for future LSI interconnects.

The advantage of CNT-bundles is their low resistance, which may be the solution to the problem of high resistance in scaled-down vias.

5.1.7 Nanoscale magnetic devices

Manufacturing technology for high magnetic material for magnetic polarization of MRAM is under development.

Tera-level highly integrated storage with nanoscale magnetic devices is under development.

Non-volatile magnetic domain memory is under development.

5.1.8 Molecular devices

The molecular device is a new nanoscale device based on unique chemical, electrical and physical functions of the molecule

The molecular device is an attempt to apply the reactions of the molecule to the device. For example, rectification effects of 4-thioacetatebiphenyl SAM, NDR and rotaxane of molecular structure which performs switching following the voltage applied. It is similar to that of memory device or logic circuit based on semiconductor. Mechanical motion or energy conversion function that resulted from transformation of molecular structure according to light or electric energy supplied outside, can expect the optical device as well as nano machine. On the other hand, super-high sensitive and miniature sensor application technology is expected, which will be able to detect the molecular level materials by functionalizing the specific molecule sensitive to pressure, temperature, radioactivity or biochemical environment.

5.2 Scenario

5.2.1 Scenario for nanoscale non-volatile memory devices

Non-volatile high capacity memory devices are important, though they have reached their limit with traditional scale down methods for semiconductor devices. The technology of next-generation non-volatile memory devices with integration with less than 30 nm design rule is affected by nano phenomena.

For nanoscale non-volatile memory devices, physical theory for measuring reliability of PCRAM (phase change random access memory) is not known or the operating principle of ReRAM (resistive random access memory) is not known.

In particular, PCRAM is approaching practical use, but standard methods for evaluation of one year or ten year storage capacity have not been established. Since an evaluation method is necessary for launching the product into the market, physical modelling and theory must be established for this to remove uncertainty of nano products.

In the case of nanoscale devices, the performance of one cell cannot represent the performance of the whole device. The percentage of parasitic elements at the nanoscale has been expanded, and in the case of flash memory devices, the interference phenomenon between cells is critical. It is required to establish standards for evaluating, calculating and controlling the variability of cell features or interference between cells as well as performance evaluation of a single device in terms of nanoscale non-volatile memory devices.

It is essential to develop a measurement standard TEG (test elements group) that can closely indicate the key control characteristics for new nanostructures or nanomaterials.

Since the variability of devices increases as they transition to the nanoscale, it should be actively approached from the area of nano science and technology, which can remove the uncertainty of nanoscale devices. It is essential to standardize evaluation technology to address variability of nanoscale devices, to explore nanotechnology that can control or inhibit the variability of nanoscale devices with bottom-up or top-down methods, and to standardize IP or nanoscale architecture allowing variability. It is desirable to start standardization for design, physical modelling and evaluation technology for variability of nanoscale devices, with focus on the non-volatile memory devices that are positioned to lead in the market. Variability has already become a serious problem.

5.2.2 Scenario for nanostructure electronic materials

Standards and measurement systems are required for accurate comparison and analysis for new materials or nanostructure based nanoscale devices that exceed the economy and performance of existing semiconductor devices.

No novel or core technique has appeared in interconnect technology between new nanomaterials or nanostructures. Individual performance of unit nanoscale devices may not be meaningful unless new technology nanoelectronic device interconnects is achieved.

Nanotubes and nanowires illustrate the disadvantage of variability. For example, nanotubes can show various features of band structure of semiconductor depending on chirality of the nanotubes, and it can cause severe variability among nanoscale devices. Accordingly, nanotubes and nanowires for electronics need standardization for evaluating variability.

5.2.3 Scenario for nanoscale interconnects (CNT)

CNTs exhibit excellent electrical properties that include current densities exceeding 10^9 A/cm^2 and ballistic transport along the tube. Because of these factors, with their large electro-migration tolerance and low electrical resistance, CNTs can be used as nano-size wiring materials, and are thus becoming potential candidates for future LSI interconnects.

Much effort has been made to produce CNT vias, which use bundles of MWCNTs, as vertical wiring materials. The advantage of CNT bundles is their low resistance, which may be the solution to the problem of high resistance in scaled-down vias.

In our estimation, we assumed that CNTs have a quantum resistance RQ = h/4e2 = 6,45 k (conductance GQ = 2GQ0 = 4e2/h, which reaches the maximum conductance limit for ballistic transport in two channels of a CNT), that current flows through each shell of MWCNTs, and that ballistic transport does not depend upon CNT length.

According to many results obtained so far, the conductivity of CNT bundles is strongly dependent on CNT density (filling rate). However, there is a lack of information on CNT density due to the absence of a standard measurement technique.