A Vision of Materials Science in the Year 2020

(Excerpts from the "2020 NIMS Policy Paper")

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Independent Administrative Institution
National Institute for Materials Science

http://www.nims.go.jp/eng/

Preface

Profile

Teruo KISHI

As the first President of NIMS, Prof. Kishi is promoting a variety of innovations in research systems, evaluations, the operational aspect, etc., while also serving concurrently as member of the Basic Policy Research Committee of the Japanese government's Council for Science and Technology Policy. Prof. Kishi was also Vice President of the Science Council of Japan from 2003 to 2005.

His professional field is strength/nondestructive evaluation of materials.

The National Institute for Materials Science (NIMS) is an independent administrative institution engaged chiefly in basic research and fundamental R&D on the science and technology of materials. The Institute was established on April 1, 2001 as the result of a merger between the National Research Institute for Metals and the National Institute for Research in Inorganic Materials. NIMS has concluded its 1st Mid-Term Program of fiscal 2001 to fiscal 2005 and has established its base as a multidiscipline laboratory that covers materials as a whole. During the 2nd Mid-Term Program (fiscal 2006 to fiscal 2010), NIMS aims to be an international and core institution in materials science with two priority R&D regions, "Nanotechnology-driven advanced materials researches" and "Advanced materials researches for social needs."

There is apparently great significance in considering the middle- and long-term future prospects of NIMS through a global perspective at this time like these. By the way, the current age range of NIMS researchers is about thirty to sixty years old and the average age is forty five years old. There is also significance in NIMS' considering the segmenting of its future schemes into fifteen years as they will see a turnover of half of its members every fifteen years.

It was from a viewpoint such as above the NIMS 2020 Study Committee was established as a president's advisory board in November 2005 in order to examine "the ideal form of NIMS in the year 2020" along with the compilation of the "NIMS Policy Paper 2020".

This booklet is an extract of the future vision of materials science in the year 2020 from the contents described in the "NIMS Policy Paper 2020" above. The NIMS 2020 Study Committee consists of mid-level and junior researchers of NIMS (60 years old or younger in the year 2020), external knowledgeable persons from a national university (University of Tsukuba) and an Independent Administrative Institution for R&D (The National Institute of Advanced Industrial Science and Technology) who are in close collaboration with NIMS, operational front members of NIMS who serve as committee members, and the vice president in charge of research who serve as chairperson. This booklet has been compiled upon discussions on the future vision of the materials science in the year 2020 based on comprehensive examinations through data produced by dense discussions in all eight committee meetings and from sources such as the results from the questionnaire that was given to all NIMS staff members.

New materials are created through the steady advancing of nanotechnology as elemental technology. It is the mission of NIMS to develop it into a wide area of research that includes information technology, biotechnology, and environment and energy technologies, and to contribute to the building of a sustainable society. By incorporating organic materials and biotechnology as well as metals and ceramics in the creation of new materials, we are attempting to create boundary regions and interdisciplinary regions involving these various fields. We want to open up new fields which use the technology called nanotech by integrating various areas of materials science that have evolved in separation until now. In other words, in addition to the conventional image of fusing or integrating several kinds of materials, we are promoting research with the aim of creating materials that will result in true innovations. We want to promote research that leads materials sciences of the world through this.

Contents

1. Introduction

Curbing global warming and reducing the emission of CO_2 are among the most important social and economic problems that need to be addressed from a global perspective. Since the 1970s, Japan has taken the initiative in the saving of energy and the development of natural energies as strategic issues. Today we have globally renowned technologies for saving energy and creating new energy while emitting comparatively small amounts of CO_2 (on a per-capita basis) despite being one of the most industrialized countries. As shown in Fig. 1, such worldwide issues as conservation of the global environment, measures to deal with the declining birthrate/aging society, and effective utilization of energy resources have become conspicuous much earlier in Japan than in other countries.

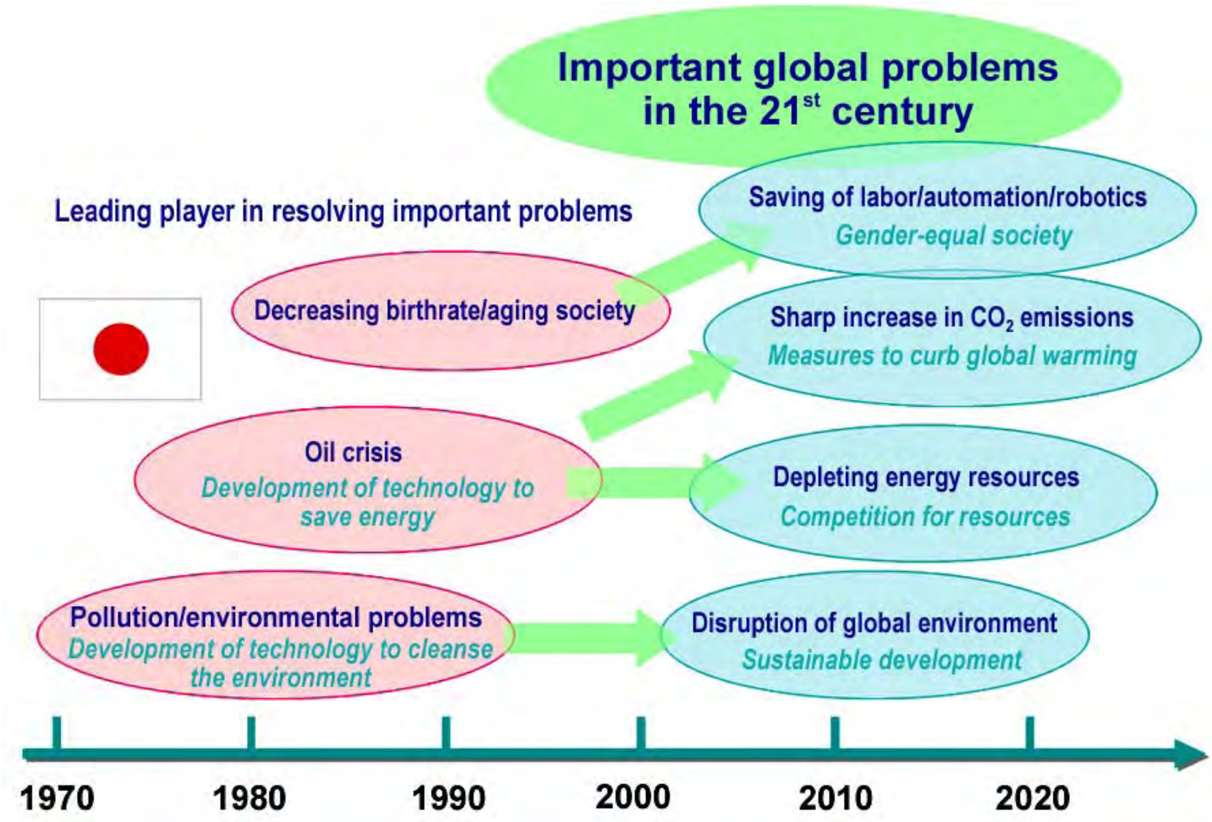

Fig. 1 Activities to resolve important problems in Japan and other countries

Concerning important global problems, effective solutions to which have yet to be found anywhere in the world, Japan should develop innovative technologies to help resolve them, promote those technologies throughout international society, and establish de facto standards for the building of a sustainable global society.

In order to resolve the diverse problems we are faced with this century and build a society that can achieve sustainable growth, it is essential to introduce innovations so as to maintain and improve our highly original and superior scientific and technological strengths and industrial competitiveness. The National Institute for Materials Science（NIMS） aims to foster a society that can achieve sustainable growth through the materials research as an important factor in the progress of science/technology and a valuable source of innovation in various industrial applications.

2. Vision of Materials Research in 2020

Generally speaking, it takes a long time before a new substances/materials can be put to practical use, from the basic study and fundamental R&D until final product development. Research on substances/materials is merely the starting point for the R&D process as shown in Fig. 2.

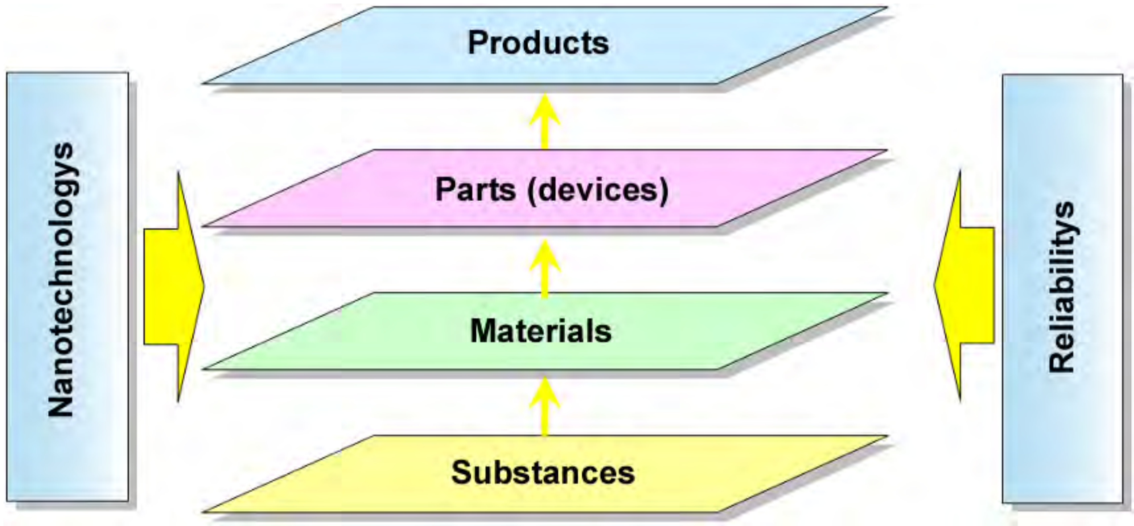

Fig. 2 Position of substances/materials in the R&D process, from basic study to product development

Specifically, new substances evolve from research on existing substances to create new substances while searching for new functionality (1st stage). Of these new substances, those which appear to be socially and economically useful are subjected to further research as materials (2nd stage). Here, research into the process to create the new material and enhance any useful functions and performance exhibited by the material is important. New materials which display superior functionality and performance to existing materials and which can be produced efficiently are subjected to research as parts (devices) (3rd stage). The research on parts (devices) is intended to put these new materials to practical use. At this stage, it is important to pay due attention to social and economic needs for new materials and consider efficient parts manufacturing processes and total system performance in close cooperation with industry. In the final stage of products development (4th stage), most effort is directed at production. At this stage, industry takes the lead in terms of R&D, including that to ensure the safety and reliability of the substances, materials and parts. On the other hand, substances and materials can be classified according to their social and economic uses. For example, there are information communication materials, automotive materials, aeronautical materials and environmental materials. It is important that this classification of materials by use be compatible with industrial needs.

2.1 Vision for Entire Science and Technology

Science and technology can be divided into basic science, intended primarily to establish the truth, and applied science and technology, which are intended primarily to meet specific social and economic needs. The direction of scientific and technological development is influenced by various economic factors and conditions, as well as by national and social needs. Therefore, in order to predict where science and technology will be in the year 2020, it is first necessary to make some social and economic forecasts for the coming 15 years.

According to some social and economic forecasts, by 2020, global warming and the depletion of fossil fuels will be major social problems on a global scale. In addition, in the most industrialized countries, the declining birthrate, aging of society, and hikes in medical and social security expenses, etc. will become conspicuous. In terms of major economic movements in the face of such social situations, the following are expected; i) an increase in the proportion of foreigners, women and elderly people employed, ii) a shift in emphasis for medical services from treatment to early diagnosis/prevention, iii) the development of technologies to help with household tasks and nursing care (robotics, etc.), and iv) the use of alternative energies (solar power, fuel cells, wind power, etc.) in place of fossil fuels will be accelerated by 2020. On the other hand, thanks to the continual progress of science and technology, the present Internet society will evolve into a ubiquitous information society that permits anyone to gain access to desired information anytime and anywhere and, by 2020, a sophisticated information society that delivers specific tailor-made information to each individual user will be available on a global scale, causing the social environment to change dramatically.

As the prime mover for such a drastic change in the social environment, applied science and technology will positively promote new growth industries and highly competitive industries. The four priority fields (life sciences, information communication, environment and nanotechnology/materials) that have been adopted as project themes by 2010 in the National Government's 3rd Science and Technology Basic Plan and another four fields (energy, manufacturing technology, social infrastructure and frontiers) have close relationships with the industrial sectors that are expected to grow markedly in view of present social and economic demands. In particular, it is considered that life sciences, information communication, energy and the environment will remain important fields even in 2020 and that applied science and technology should play a vital role in those fields.

While applied science and technology develops hand in hand with society, basic science, as the basis for any nation living on the science and technology it develops, provides extensive support for science and technology as a whole. Basic science by which truth is sought not only increases the intellectual property base shared by humankind. As basic science progresses, it will also produce seeds for dramatic technological innovations in the future, helping to create entirely new industries. Furthermore, it can be expected that technology derived from basic science will enable the creation of new industries and enhance value. Even if we limit ourselves to basic science in the field of materials, it is not easy to picture the situation in 2020. In the next section, we shall take a general view of the future research on materials that will be carried out amid the ever-swelling wave of globalization reflecting the individuality of Japan. Later, in Chapter 3, we shall discuss those research fields to be prioritized regarding the application of nanotechnology to materials that is expected to extend the frontiers of basic science and in the research on environmental and energy materials and material reliability, the social demands for which are expected to continue expanding till 2020.

2.2 Vision of Materials Research in Japan and the World

Even in 2020, materials research can be positioned as a key technology for cutting-edge industries that take the initiative in building a sustainable society. Namely, by 2020, it is expected that the whole world will enter into an age of grand economic competition. It is, therefore, essential for Japan to reinforce its internationally competitive industries in terms of both quality and quantity by that time. Economic globalization is promoting the rapid industrialization and economic growth of China, India and other populous countries, prompting those countries to develop and maintain their social and economic infrastructures and stimulating demand for the material industries that supply steel, cement, and petrochemical products, etc. These materials industuries are a key technology for the transportation equipment industries, such as the automotive industry. It is expected to develop the new structural materials necessary for the development of next-generation transportation equipment that are lighter, stronger, tougher and more durable while consuming less energy. It is important for those high-tech materials industries to conduct basic and fundamental research in the field of materials and develop new materials that bring about industrial innovation.

There is fierce competition in the highly industrialized countries in the semiconductor/electronics, information communication, energy, and life-science industries, etc., which are regarded as the key industries in the 21st century. In those key industries as well, the most advanced manufacturing process technologies that employ nanotechnology and new materials that offer innovative new functionality are key to technological innovation. Thus, in order for Japan to maintain and improve the competitiveness of those key industries expected to support a sustainable society in 2020, it is necessary to be mindful of the strategic importance of basic research and fundamental R&D to the development of next-generation nanotechnology and for the creation of new materials (see Fig. 3).

Fig. 3 Position of nanotechnology and the science and technology of materials as key technologies in the most advanced manufacturing to bring about innovation

Japan boasts ultra-precise processing and measurement technologies as represented by nanotechnology, advanced industrial technologies to create a wide range of materials, and high levels of skill and knowledge in disciplines related to materials, from basic research to practical application. In an age of global competition, making effective use of these advantages in nanotechnology and materials to reinforce the competitiveness of the existing key industries and growth industries that are expected to shoulder the next generation is the strategy our country should adopt.

Organic materials and biomaterials will find many diverse industrial applications and will be able to develop various new functions through structural control at the nano level. It is considered, therefore, that these will represent a major field of research into materials in 2020. In terms of semiconductor-related materials that are socially and economically important as information communication and energy transformation materials, it is considered that related research will become more extensive in the future since they allow for discrete innovations through the application of nanotechnology. With respect to composite materials made of various organic and inorganic materials, research on these as functional materials and intelligent structural materials in the fields of environment/energy and reliability will be expanded in the years ahead.

With the imminent advent of an environmentally conscious but aging society with sophisticated information access, there is expected to be more research into functional materials in 2020 than today, since demand for biomaterials to implement advanced medical care, ubiquitous functional materials (optical materials, magnetic materials, semiconductor materials, etc.), and environmentally conscious functional energy materials for solar power generation, etc. will expand noticeably. With respect to structural materials as well, it is considered that the fusion of function and structure (e.g., imparting intelligent functions, such as failsafe capabilities, to materials by combining different substances) will proceed.

3. Research Fields to be Prioritized by 2020

3.1 Research into Nanotechnology-related Materials

Nanotechnology is a general term for the science and technology involved in creating, measuring, assessing and predicting substances/materials (nano-materials) and functional elements (nano-devices) in the order of nanometers (billionths of a meter). Since nano-materials and nano-devices are expected to be capable of developing discrete characteristics and functions (in this respect, they are different from macro-materials and macro-devices), government-led R&D into them is forging ahead in many countries since they are an important key technology in the 21st century.

In order for Japan to promote the building of a sustainable society, it is necessary to maintain and improve the competitiveness of its high value-added industries, such as the information communication industry, precision-machinery industry, high-tech transportation equipment industry and complex pharmaceutical industry. The technological foundations that allow for innovations in those high-tech industries are ultra-precise manufacturing technology and new materials that can develop innovative new functions.

On the other hand, in seeking fundamental truths or exploring unknown realms of learning, analyzing substances at the atomic level is essential. Materials science based on quantum mechanics was established in the 20th century and provided a base on which to understand various characteristics developed by individual substances and materials. Nano-measurement technology, developed at the end of the 20th century, has rapidly become a powerful tool for visualizing individual atoms in actual space and clarifying the electron state. This new technology has made it possible to verify atomic-level theories which have been hard prove by direct experimentation. The advent of atomic-level measuring technology soon led to the development of an atomic-level substance-creating technology, forming a set of technologies collectively termed nanotechnology. In addition, thanks to the progress of nanotechnology in extreme environments, new physical phenomena beyond the bounds of conventional understanding have been identified. As a result, a new discipline (nanoscience) to clarify the origin of this diversity of substances is being established.

(1) Key components of nanotechnology

The key components of nanotechnology for the measurement, creation and prediction (simulation) of materials at the nano level can be considered as “key technologies” for making discrete innovations in research into materials, from basic science to applied research. In the paragraphs that follow, we shall describe the latest trends in the individual key components of nanotechnology and their expected status in 2020.

<u>1) Nano-measurement technology</u>

The key component of nanotechnology, and the first to be developed, was one for analyzing and evaluating nano-structures. This key component is called nano-measurement technology. The scanning-type tunnel microscope invented in the 1980s made it possible to directly visualize a single atom for the first time. It can be said that this invention paved the way for the subsequent progress of nanotechnology. Nano-measurement technology is a technology that has a spatial resolution at nanometer level and that allows for plural measurement of shape, functions, and physical properties, etc. So far, a wide variety of microscopes with atomic resolution, such as the transmission electron microscope and the scanning-type probe microscope, have been developed. It is expected that by 2020, nano-measurement technology will be used not only for identification of the types of individual atoms but also for sophisticated nano-measurements, such as measurement of electrical conductivity on a nanometer scale, measurement of atomic resolutions of biomaterials, and high-resolution measurement of bio-systems.

2) Nano-creation technology

Nano-creation technology is used to process, create and form nano-structures. This technology can largely be divided into top-down types that permit processing the entire macro area of the structure and bottom-up types that assemble the structure from the atomic/molecular level. For the top-down type, various processing and forming methods using electron beams, ultraviolet rays, X-rays, ion beams, and lasers, etc. have been developed. With this type, the physical limit of processing accuracy is approximately 10 nm. With the bottom-up type, by employing a scanning-type probe microscope, it is possible to perform various kinds of nano-processing and nano-creation, such as positional and structure control at the single-atom level and nano-lithography. The top-down type and bottom-up type can be used effectively in combination in such a way that they complement each other. Therefore, it is considered that nano-creation technology in 2020 will attain a processing accuracy of approximately 1 nm or less through the fusion of top-down and bottom-up types and provide a new processing technology for next-generation nano-electronics. With regard to this technology, it is also important to use a self-organizing mechanism for orderly arrangement of atoms and molecules based on their mutual reaction.

3) Nano-simulation technology

Nano-simulation technology is a large-scale, high-speed computing technology applied to nanotechnology. It permits designing and simulating the optimum construction and expected physical properties and functions of the nanostructure to be created and thereby improves the efficiency of the development process significantly. The nano-simulation technique, which harks back to basic theories of physics, such as quantum mechanics, has been used as an effective means to understand the basic characteristics (physical properties), structures, and conditions, etc. of substances and materials. In the past, because of comparatively slow computing speeds and insufficient memory capacity, the technique was considered applicable only to model systems composed of relatively small numbers of atoms. Improvements in computer performance, especially computing speed and memory capacity, in recent years have been remarkable. The Earth Simulator—Japan’s fastest supercomputer—boasts the world’s third highest computing speed (40 teraflops, that is, 40 trillion floating-point operations per second) and has a main memory capacity of 10 terabytes. Such a dramatic improvement in computing speed has made it possible to perform large-scale, highly accurate calculations. As a result, the application scope for simulations on the structures and functions of substances and materials has been expanded from simple atoms/molecules to complicated nano-structures.

Simulation techniques include first principle calculations that handle the properties of materials at the atomic level; molecular dynamics calculations that handle the group motions of atoms and molecules, etc.; the Monte Carlo simulation; the phase field method that permits predicting the time-serial change in material structure from the nano- to meso-scale; the finite element method that handles macro materials; and the thermal statistical dynamics calculations; etc. Such a multi-scale simulation, which can handle a wide range of structures and physical properties from the atomic to macro levels, is very useful in research on substances and materials. Therefore, R&D on multi-scalar simulations has been actively conducted.

It can be said that thanks to the development of various analytical techniques, such as those mentioned above, and the marked improvement in computing speed, the prediction accuracy for the structures and functions of materials using large-scale, high-speed simulations has reached a practical level. For example, by predicting the functions to be developed by a system of substances and materials to be newly synthesized by applying such a simulation, it is possible to narrow down the system that has to be synthesized. This means that a material suitable for the purpose can be created efficiently. Thus, large-scale computational simulations have become an indispensable tool for research into materials.

Today, it is possible to design the optimum atomic arrangement/construction and creation/synthesis processes, as well as to predict the functions and physical properties of various structures, from surface reconstructions to massive protein molecules. Now that construction of a faster next-generation supercomputer with a larger memory (petaflops class) is planned, the computing speed and available memory capacity will improve dramatically. It is considered, therefore, that the applicability of nano-simulation technology and computing accuracy is certain to improve and that first-principle computational simulations of nano-biomaterials and computer simulations of nano-creation processes will be performed in 2020. It is also assumed that virtual experimentation, which was virtually impossible before, will be almost routine by that time. As a result, nano-simulation technology will increase in importance.

By 2020, the three fundamental technologies under the heading nanotechnology as described above will be thoroughly integrated and an efficient system which permits the consistent implementation of nano-simulation (Plan), nano-creation (Do) and nano-measurement (See) will be available. As a result, it is expected that research into nanotechnology-related materials and the introduction of innovations will be promoted (see Fig. 4).

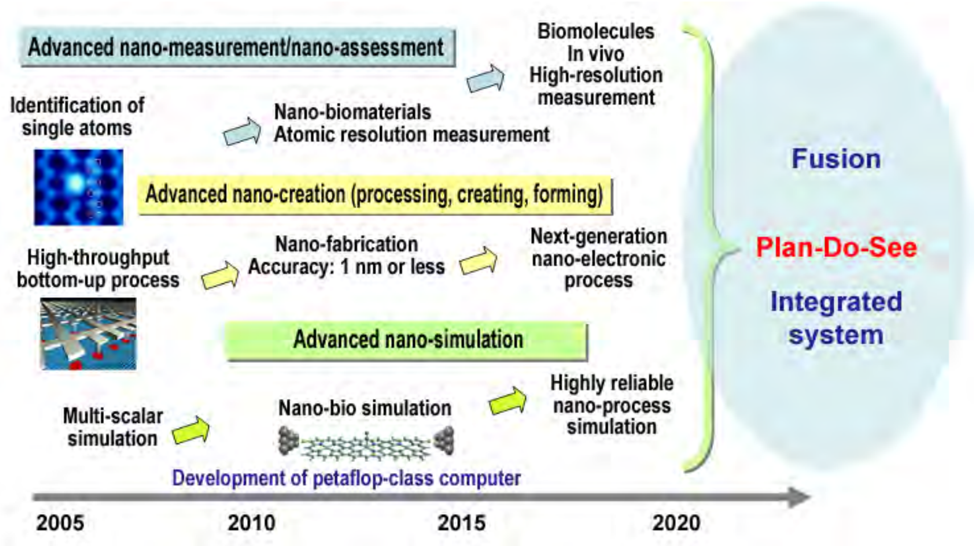

Fig. 4 Predicted development of three key components of nanotechnology
An integrated system of nano-simulation, nano-creation and nano-measurement (plan-do-see) will be available by 2020.

(2) Nano-biotechnology

Nano-biotechnology is a multi-discipline research realm intended to apply nanotechnology to medical care and biology. It is a field that is expected to grow markedly in the future. In terms of applications, it can largely be divided into the medical care and measurement fields. In the paragraphs that follow, we shall discuss the major research themes in each field with a focus on the present conditions and materials called for in 2020 (prediction).

1) Medical care field

i) Artificial internal organs: With the progress of regenerative medicine, research into artificial internal organs has advanced markedly. At present, simple tissues such as artificial bone and cartilage are the main research themes. By 2020, however, complex tissues, such as the liver and kidney, will become major research themes. It is to be desired that biodegradable tissue-inducing materials that simulate living body tissues should be developed.
ii) Drug delivery systems (DDS): The research field for DDS is highly marketable and important in the pharmaceutical field. At present, high-molecular polymeric micelles are closest to commercialization. All other materials are still at a fundamental research stage. Present research is focused on DDS carriers for injections. By 2020, however, percutaneous DDS drugs will probably be the main research theme. In addition, it is expected that research into cell therapy to directly treat cells using technology as a by-product of such DDS research will be realized by that time.
iii) Implant-type sensors: At present, the implant-type sensor that is closest to commercialization is a glucose sensor that utilizes a bio-fuel cell. By 2020, research on five-sense sensors using bio-fuel cells will become mainstream. In this respect, it is to be desired that materials with a high degree of biocompatibility should be developed.

iv) Treatment devices: At present, research on the miniaturization of devices used in endoscopic operations, etc. is being conducted. Developing an angiographic endoscope and suchlike requires further technological breakthroughs.

2) Measurement field

i) Biosensors: At present, research into biosensors using enzymes and antibodies, etc. is mainstream. By 2020, however, research into the use of yeast cells and human cells as sensors will gain ground. There is a good possibility that cell chips will be put to practical use by that time. In this respect, it is important to develop an interface between the cell and the sensor.

ii) Nano-cell mapping: At present, obtaining information from the cells of living organisms using a carbon nano-tube, etc. is still at the fundamental research stage. Nano-cell mapping might be applied in cell therapy or suchlike by 2020. In this case, it is necessary to clarify the cell toxicity and safety of nano-substances and nano-devices used.

iii) Bioelectronics: At present, bioelectronics is at the fundamental research stage. By 2020, it is very likely that the results of the present research will be used in clinical examinations and health care, etc. It is important to develop materials for interfaces between biological parts (DNA, proteins, cells, etc.) and electronic parts.

(3) Nano-information communication technology

In the field of nano-information communication, efforts are being made to improve the international competitiveness of the information communication industry, one of Japan's most important high-tech industries, by using fundamental materials technologies based on nanotechnology.

With the development of an advanced information-processing society, information communication materials technology must become still more sophisticated (more functions, more speed, greater degree of integration, less power consumption). Since meeting those requirements necessarily puts the device characteristic size into the nanometer region, advanced fabrication technology applicable to nano-region and nano-material science and technology to manipulate and utilize the unique phenomena in the nano-region are indispensable. The nano-information communication materials required include: semiconductor device-related materials to increase the speed and degree of integration of semiconductor LSI (large-scale integration) while reducing the power consumption of LSI; optoelectronic materials to increase the speed of optical communication networks and improve the efficiency of light-emitting devices; and magnetic and spin-electronic materials for large-capacity recording devices; etc.

1) Realization of ubiquitous information society

Our modern-day information society – realized by the improvement in performance and the increase in degree of integration of the transistor invented in 1947 – will continue to develop. By 2020, it is expected that the next-generation information society based on an upgrade to ubiquitous computing in which anyone can gain access to information desired anytime and anywhere will arrive. On the other hand, it is anticipated that the present refinement of silicon electronics will reach its limit by 2020. Therefore, in order to realize the next-generation information society, the introduction of a newer concept than conventional silicon electronics, whose performance has been continually enhanced, is indispensable. Realizing a ubiquitous information society requires the development of a compact, high-performance, high-function arithmetic processing device, wearable devices made of extra-thin, plastic display elements, etc., a communication device designed for a high-speed communication network, a sensing device to act as a human interface, and a quantum cipher communications system to maintain information security, etc.

2) Development of new nano-functional materials

Up to now, the development of devices has focused on the enhancement of functions and an increase in the degree of integration through refinement. By 2020, it is expected that the central theme for innovation in electronics technology will be the manipulation not only of electrons in the nano-region (nano-electronics), but also of light (nano-photonics), atoms, etc. in the nano-region and that most emphasis will be placed on introducing new concepts and putting them to practical use. For example, it is desired to develop and put to practical use molecular electronics, spin-electronics, carbon electronics, atomic electronics, and quantum computing, etc. as devices operating under new concepts (see Fig. 5). For those devices based on new operating principles, such as a device for controlling the movement of a single electron and a device using a single molecule as its functional element, new materials and structures different from those for conventional devices will be used. Therefore, it is considered that the development of new nano-functional materials will become increasingly important.

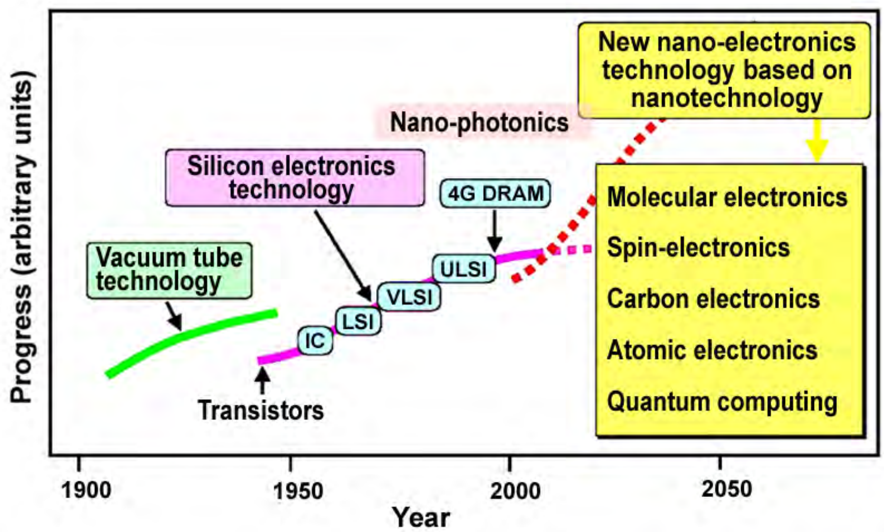

Fig. 5 History of development of electronic devices and prediction of development of new devices

It is also nano-level material creation technology that will support the competitiveness of the optoelectronic industry in 2020. For example, by fusing advanced nano-material creation process technology for highly efficient wavelength changeover materials, non-indium based transparent conductive materials, carbon nano-tubes, solid ultraviolet laser materials, white LED materials, and photonic crystal materials, etc. with optoelectronic technology, it is considered possible to put new communication devices, display elements, and light-emitting devices, etc. to practical use.

3) Materialization of next-generation storage devices

On the other hand, in order to materialize next-generation storage devices (large-capacity, high-speed recording devices, ultra high-density nonvolatile memory, etc.) which are indispensable for an advanced information society, it is necessary to have sophisticated nano-creation technology to prepare high-performance magnetic materials whose tissue is controlled at the nano level, and spin-electronic materials produced by a nano-level lamination process, etc. The possibilities of developing devices through the introduction of a new nano-functional structure and nano-materials are limitless. Such devices include highly dielectric, ultra high-density memory based on nano-domain engineering and large-capacity, ultra high-speed optical communication devices using nano-glass.

From the standpoint of putting those new devices to practical use, it is important to develop a hybrid technology with silicon electronics. In 2020, higher functions will be required of silicon electronics in our advanced information society. In order to meet such requirement, it is essential to combine the new devices mentioned above with silicon electronics. In the development of technology to combine the new devices and silicon electronics, it is necessary to ensure the compatibility of the materials and nano-processing process, as well as device structures. It is expected that materials will play an important role in those fields too.

(4) Creation of new materials and control of nano-scopic textures

Nano-structured materials display exceptional performance and offer innovative new functions. As a source of new materials to shoulder the future, they are attracting attention from various quarters. In this category, all materials—metallic, inorganic, organic, polymeric—are included. Their constituent elements include: low-dimensional nano-substances, such as nano-tubes and nano-sheets; molecular substances, such as fullerene, organic molecules, giant molecules and supermolecules; nano-fibers and nano-particles; etc. There are cases in which DNA, protein or cellulose is a constituent element. By texture type, the materials can be classified into nano-composite materials, nano-pore materials, nano-phase separated materials and soft matter (gels, cell membranes, etc.). In nano-structured materials, the structure and function are inseparable. Hence, in order to implement nano-level structural control, it is essential to have a sophisticated manufacturing process in the first place. Fig. 6 shows typical nano-structured materials, their constituent elements, forms, textures and functions.

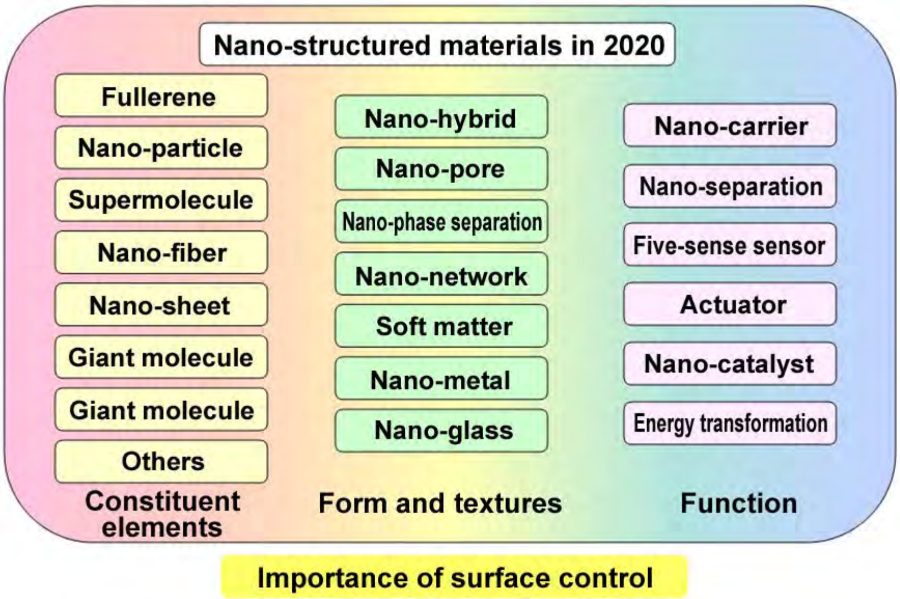

Fig. 6 Typical nano-structured materials, their constituent elements, forms, textures and functions

In order for nano-structured materials to develop entirely new functions, it is especially important to control the nano-structure at the interface between metal and semiconductor, and between organic and inorganic materials, etc. In research on biocompatibility and tribology, etc., control of the surface interface, including the nano-structure of liquids, is important. Control of the nano-structure at the interface has a direct connection with control of the electron density at the material surface and the oscillating condition of atoms. This belongs to the area of physical and chemical research that deals with adsorptions and catalyst characteristics, etc. On the other hand, the surface modification of a nano-substance provides an important approach to the development of new materials. Coatings on a nano-tube, chemical modification of its interior space, fixing of protein to a nano-particle, and nano-fibers carrying microorganisms are examples of this.
Nano-structured materials cross extensively over many different research fields, and are studied in earnest in each of those fields. It is considered that such research will be conducted in the following directions in the future.

1) Development of new materials

Strictly speaking, there are not many examples of “materials whose structure is controlled at the nano level.” With the progress of nanoscience, however, it is expected that the development of new nano-structured materials will be activated in various materials fields in the future.

2) Development of manufacturing processes suitable for specific uses

In order to promote the development of the new nano-structured materials mentioned above, it is vitally important to develop a manufacturing process suitable for a specific use or purpose.

Such concepts as self-organization, transcription, duplication and autonomic systems stemming from biology provide a valuable approach to this problem. By extending those concepts widely to nano-substances, it is considered possible to develop innovative new manufacturing processes. As concrete development targets, nano-composition/dispersion technology for metals, ceramics, giant molecules, etc., interface/surface control technology to control the flow of electrons and energy, biomimetic form control, and nano-separated film manufacturing technology, etc. can be cited. When these processes are combined with the top-down nano-forming and nano-processing technology, major innovation is likely.

3) Significant enhancement of material functions by nano-structuring

It is evident that the ultimate objective of nano-structuring is to significantly enhance the functions of materials, as in the development of new materials with excellent mechanical properties (tensile strength, toughness, etc.) or demonstrating excellent electronic and optical characteristics. Nano-structuring is considered very effective to improve numerous different material characteristics—mechanical, electrical, magnetic, optical, and biological.

4) Direction of R&D on nano-structured materials

In terms of nano-structured materials, the research fields that should be given special priority until 2020 are energy and the environment. In the energy field, it is important to utilize recyclable resources so as to build a sustainable society. Hence, developing nano-structured materials that help promote the use of solar energy and biomass should be one major theme. Needless to say, it is also important to develop materials for fuel cells and materials which can be used in equipment to generate and store hydrogen. In the environmental field, it is extremely important to develop catalysts to build new substance circulating systems. In particular, development of a wide variety of nano-structured catalysts, from solid catalysts to enzymes and yeasts, is awaited. In addition, the extensive application of photocatalysts is an important task to tackle. As another important research field that helps us move away from fossil fuels, nano-separated materials and carriers can be cited. In fact, nano-membrane separation, which is essential for small-scale distributed chemical processes, and nano-carriers, used to transport and store chemical substances, are emerging as important research themes.

3.2 Research into Materials that meet Social Needs

(1) Environmental and energy materials

Reducing the emission of CO_2 and other greenhouse gases has long been called for. On the other hand, various global environmental problems have been reported in recent years—the depletion of natural resources due to mass production and mass consumption, disruption of the natural environment, and environmental pollution from metal production processes, etc. In the development of materials in the future, it is necessary to pay more attention than ever before to their effects on the environment. Environmental materials can largely be divided into three types: resource-saving materials, low environmental impact/environment-purifying materials and clean energy materials.

1) Resource-saving materials

Resource-saving materials are those that help preserve energy or natural resources. For example, consider transportation equipment, such as automobiles, airplanes and vessels. By improving their fuel efficiency, it is possible to reduce the consumption of fuel and the emission of CO_2. In order to improve fuel efficiency, it is necessary to reduce the weight of materials used without sacrificing safety and improve the thermal efficiency of the engine. Thus, it becomes even more important to develop new materials which are higher in specific strength and specific elasticity, thinner, more heat resistant, and so on. In addition, prolonging the usable life of new materials helps to utilize natural resources more effectively and reduce energy consumption in the manufacturing process. Therefore, it is also important to conduct research into new materials which offer greater longevity and new methods for inspecting material deterioration.

2) Low environmental impact/environment-purifying materials

Low environmental impact materials are those which have comparatively small impact on the environment throughout their life, from production to scrapping. In view of our limited and valuable natural resources and the constraints on the environmental capacity to receive waste, those materials are designed so that they can be recycled. In addition, they are manufactured using a process which has minimal impact on the environment. From the standpoint of recycling those materials, it is to be desired that they should be of simple alloys containing no harmful substances and few alloying elements. In conventional alloy designs, many different elements are added to improve material performance. However, the more elements that are added, the more difficult it becomes to separate them out. This means that the energy and cost involved in recycling the material increase. Therefore, it is necessary to review the environmental impact of the existing materials and replace them with new materials having less environmental impact where appropriate. Up to now, research on materials has focused on their “making”. From now on, we must consider “breaking” as well. In developing a new material, it is necessary to pay due attention to its recyclability. In the future, it will also be important to develop photocatalysts and other environment-purifying materials which help purify water, air, etc.

3) Clean energy materials

Global energy consumption has been increasing year by year. In 2000, the world’s energy consumption was about 1.8 times that in 1971. This trend will continue in the years ahead. It is expected that in 2020, the world will consume 1.4 times more energy than in 2000. On the other hand, fossil fuel resources are not limitless and may be completely depleted within this century. Japan depends on fossil fuels for about 50% of its energy (nearly 80% when oil and natural gas are included). Since the country imports the vast majority of its energy resources, it has to find new energy resources before fossil fuel resources are depleted.

Hydrogen is one of the promising new energy resources. Developing new materials to utilize hydrogen is the key to putting this new energy to practical use. For example, fuel cells that have been attracting much attention in recent years generate electricity through the reaction

between hydrogen and oxygen. The hydrogen it uses needs to be manufactured from methanol or natural gas, etc. It is, therefore, important to develop materials for manufacturing hydrogen, such as catalysts and hydrogen-separating membranes. In order to use hydrogen safely as a source of energy, it is also necessary to develop new materials for equipment to store the hydrogen.
In addition to hydrogen, solar light, solar heat and other natural energies will be used more positively in the future. From the standpoint of promoting solar power generation by using solar cells, it has become necessary to improve the energy transformation efficiency of existing silicon-based semiconductors and compound semiconductors, cut theirs costs and develop an effective method of storing surplus electricity. In addition, expectations are entertained of putting to practical use thermoelectric semiconductors that transform heat into electrical energy since it is a clean generation method of transforming waste heat into electricity. Superconductivity is the key technology for efficiently transmitting electrical energy over long distances since it permits the passage of large electric currents with virtually no electrical resistance. High-performance secondary batteries that can be charged and discharged repeatedly are widely used in automobiles, cell phones, and notebook personal computers, etc. For these products, it is important to develop new materials which offer higher performance and longer life.

(2) Research into material reliability

Even in modern society, there are cases in which loss of life or damage to social infrastructure is caused by an accident ascribable to an unforeseeable breakdown of some material. Despite many years of research conducted into materials in the past, much is still unknown about the fracture mechanisms of materials. Therefore, it is necessary to conduct research into the reliability of materials so as to predict deterioration and damage to materials which are used for a prolonged periods and prevent them from breaking. For more than 30 years, NIMS has carried out research into the safety of transportation equipment, power plants, chemical plants, etc. It has collected and published systematic data about creep, fatigue, etc. for many different materials in the form of material data sheets. In addition, it has devised various new methods of testing and assessing materials, carried out research into the mechanisms of damage and fracturing of materials and developed highly–reliable materials, with tangible results. These achievements by NIMS have been highly evaluated for their contribution to society. For example, the results of research carried out by NIMS are fully reflected in the review process for national standards and specifications. In view of the anticipated changes affecting society, such as switching to next-generation energy, global environmental problems, and the aging of society, etc., activities to improve the reliability of materials and thereby contribute in the realization of a safe society that is easy to live in are called for today. In this respect, it is necessary not only to continue collecting basic data and develop a reliability assessment system, but also to promote the development of new material reliability assessment techniques and nondestructive inspection techniques as well as breakthroughs in existing technologies, including the clarification of material fracture mechanisms on a multiple-scale and the sophistication of applying nanotechnology to damage-monitoring technology and of computer simulation technology to study damage/fracturing of materials.

1) Improvement in reliability of materials used in hydrogen society

The social needs that are expected to arise by 2020 are as follows. In the field of next-generation energy, it is considered that fuel-cell cars, fuel cells for home use and hydrogen stations will gradually become more widespread. Therefore, activities to enhance confidence in a hydrogen-powered society, such as the development of technology to evaluate the fracture characteristics of materials under a hydrogenous environment, will become important. In the field of electrical power, unless new energy sources grow significantly, nuclear power and coal-fired thermal power generation will remain the mainstay even in 2020. From the standpoint of reducing CO_2 emissions, saving resources and disposing of nuclear waste, research into more efficient power plants and next-generation power plants is underway in various countries.

2) Improvement in technology to assess the reliability of structural materials

Improving technology to assess the reliability of structural materials used in high-efficiency gas turbines and coal-fired thermal power plants, high-temperature gas ovens, high-speed reactors, and nuclear fusion reactors, etc. continues to be an important task. Research on the reliability of new materials (Mg alloys, composite materials, etc.) used to reduce the weight and improve the fuel efficiency of transportation equipment is another important task to be tackled. In the future, there will be ever-increasing demand for research into the safety and reliability of biomaterials and micromechanical materials used in our aging society and materials for electronic devices used in IT society, research into the reliability of materials used in ocean and aeronautical development, research into the safety of social infrastructure (architectural structures, bridges, etc.) and research into sensor materials for detecting damage and fractures and into failsafe materials which continue to function properly even if damaged.

4. Post-Nanotechnology Initiative

Tracing back to the origin of nano-material technology, it can be seen that the semiconductor superlattice and quantum effect announced by Dr. Esaki in 1970 was the first proposal to present a concrete image. His idea was demonstrated by molecular beam epitaxy (MBE) that substantiated the nanostructure. Nearly 30 years later, as a global initiative, the idea began to spread over a wide range of fields, including biotechnology. In other words, the signs of initiatives for 2020 have already started, even though only a few people recognize them as such. It is considered that the nanotechnology initiative that began in 2000 will continue to be the global mainstream until around 2010. In this respect, it is necessary to positively grasp the signs of post-nanotechnology initiatives that should appear from 2010 onwards and to formulate a strategy to positively press ahead with the next initiative. The foundations of materials science to seek signs of new initiatives and research trends are shown in Table 1.

Table 1 Foundations of Materials Science and research trends

Foundation for research into substances/materials	Trends (factors in innovation)
Manufacturing as base on which to establish nation thriving on science and technology	International competition and peaceful coexistence Decreasing number of young persons
Development of functional materials	Diversification of nano-materials: composition, reaction and environment Compatibility with theory and computation
Development of structural materials	Diversification of compositions and reactions, increase in speed and reliability of assessment
Change in and demand for social infrastructure	Energy, environment Food, health, disaster prevention, safety

In the United States, reflecting the growing interest in energy problems, various initiatives, such as the solar cell initiative, have been proposed. As examples of candidate initiatives, the creation of a wide variety of materials, from synthetic organic materials to solid inorganic materials, and the development of high-throughput combinatorial technology applicable to functional assessment may be cited. In addition, with the advent of electronic manufacturing systems, a new research field called material informatics that quickly and effectively handles huge volumes of materials data has appeared.

In the future, Japan must take the initiative in leading the world in research into new materials and seek initiatives that should bring about breakthroughs in research on our increasingly diverse and complex manufacturing processes.

5. Postscript

On March 23, 2006, the NIMS 2020 Study Committee (Chairman: Hideomi Koinuma) published its “2020 NIMS Policy Paper” (see Note) on where NIMS should be in the year 2020 to emerge as a world-class base for R&D on materials.

This booklet presents excerpts from the 2020 NIMS Policy Paper on the research trends into materials in 2020.

Note: 2020 NIMS Policy Paper (“Aiming to Emerge as a World-Class Base for R&D into Materials”), published in Japanese by Independent Administrative Institution, National Institute for Materials Science, March 2006.

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