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Nanotechnology and Materials R&D in Japan (2015): An Overview and Analysis

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Center for Research and Development Strategy
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Executive Summary

The field of “nanotechnology and materials” is built on nanoscience based on fundamental sciences such as materials science, optics, life science, information science, and mathematical science. Nanoscience has been developed as science dealing with phenomena occurring at the nanoscale. Common basic technologies (manufacturing, measurements, and simulations) are structured on nanoscience, and applications of these technologies to materials lead to development of devices and components. Also, they become cross-cutting technologies in the fields such as environment, energy, health and medical care, social infrastructures, information and communications, electronics, and so on. Eventually, they give rise to innovation and the field of “nanotechnology and materials” plays an important role as an “innovation-engine”.

The field of “nanotechnology and materials” possesses a potential as a technological basis capable of leading the future of diverse industrial fields and carries the weight of high expectations for society. Such expectations include solutions for global problems related to the environment and energy such as climate change and depletion of the natural resources and drinking water, prevention of excessive rise of medical expenses, the improvement of quality of life of patients through early diagnoses and treatment, non-invasive diagnosis, and regenerative medical techniques in the fields of health and medical care. Growing expectations exist also in the field of information and communication technologies for advances in device technologies which realize a widespread dissemination of the Internet of Things (IoT) as well as for advances in exploration of novel materials fully utilizing data science taking into account the rapid advances in collection and processing techniques of “big data”. Through meeting these expectations, electronics, components and materials industries, which have been driving Japanese economy, possibly evolve into a new look.

While pursuing further advances in semiconductor microfabrication technologies as predicted by Moore’s law, researchers had developed techniques to observe nanoscale structures and to understand and control phenomena that occur at the nanoscale, leading to great advances in nanotechnology in the period from around 1990 to the early 2000s. Developments in semiconductor microfabrication technologies propelled progress in the digital technologies and improvements in the performance of electronic devices and, coupled with advances in network technologies, led to major innovation in telecommunications that became known as the IT revolution. In this context, nanoelectronics can be regarded as the driving force of nanotechnology during this period. However, while obstacles to further miniaturization in semiconductor microfabrication began to come to surface after the early 2000s, many researchers began attempting to produce nanostructures through self-organization using autonomous chemical reactions. During this period, there were significant developments in biotechnology, including the human genome sequencing and the emergence of iPS cells, and the roles of nanotechnology and biotechnology became an inseparable part of each other’s development. Today, humankind is facing grave issues related to the environment and energy, such as climate change, and this has further increased expectations on the role that nanotechnology and materials will have in finding solutions to these issues. However, these issues cannot be resolved solely through nanotechnology. We, therefore, have to tackle these issues with the nanotechnology combined with biotechnology, information technology, and materials science and engineering.

Concerning the materials field, Japan has played a major role in promoting R&D, particularly leading the world in the development of new materials, to support key industries of components and materials and to create new industries. Many key technologies in the field of materials were greatly responsible for some of Japan's most important inventions and achievements, including photocatalysts, lithium-ion batteries, permanent magnets, blue LEDs, and media and magnetic heads for hard disk drives.

Under these backgrounds, components and materials industries have developed numerous products centered on functional materials that claim a large share in global markets, despite the market size of each sector is small. Japan's companies also possess numerous products that have captured a large share of the global market in individual materials, such as semiconductor materials, display materials, battery materials, carbon fibers, and separation membranes for water treatment. On the other hand, Japan's once high market share in hardware such as PCs, cellular phones, and TVs has declined considerably due to fierce global competition. Japan has also suffered a loss of shares in its previous stronghold of raw materials including some of its LCD materials such as photoresist and color filters, and materials for lithium-ion batteries. The global market for batteries, power semiconductor devices, and carbon fiber composite materials, in which Japan is presently very competitive, is expected to see great expansion in the future. Needless to say, it is vital for Japan to maintain or strengthen its industrial competitiveness in these markets.

Looking at the policies and strategies of foreign countries, all the countries addressed in this report have a basic national strategy for nanotechnology or materials, positioning these fields as prior technologies. Nanotechnology is now transitioning to the next phase more than ten years after the U.S. launched its National Nanotechnology Initiative (NNI) in 2001, which created a kind of boom worldwide. A 2014 report by the U.S. President's Council of Advisors on Science and Technology (PCAST) recommended that looking ahead of outcomes, it was time for nanotechnology to transition to NNI 2.0 through systemization. In Japan, the 4th Science and Technology Basic Plan positioned nanotechnology and materials fields as common science and technology bases, while the Comprehensive Strategy on Science, Technology and Innovation (2014) redefined these fields as cross-cutting technologies. The annual administrative budget allocated for nanotechnology and materials was approximately 2 billion dollars for both the U.S. and Europe (totaling all national budgets in the EC), and was between 500 million and 1 billion in Russia, Japan, Germany, and China. While Japan's government has invested a total of about 90 billion yen in these fields, the industry has spent approximately 900 billion yen on research and development. The priority of Japan's investments has been in areas showing great industrial and social promise, including energy storage devices, power electronics, catalysts (catalysts for chemical synthesis, artificial photosynthesis/photocatalysts, fuel cells, etc.), structural materials, sensor devices (for health care, environment, and infrastructure, etc.), and the critical materials of the Element Strategy program. The U.S. has placed emphasis on advanced manufacturing (through the Materials Genome Initiative, National Nanotechnology Initiative, etc.), semiconductors (nanoelectronics), and clean energy, while Europe has focused on graphene and carbon fiber composites.

Looking at trends in human resources, membership in major academic societies involved in nanotechnology and materials fields is gradually decreasing in Japan (the decline is thought to be largest among company researchers), while membership has been increasing in major academic societies overseas. About 24,000 active members participated in annual conferences and the like in Japan related to these fields, while about 35,000 researchers in nanotechnology and materials fields published papers on these topics over the past year. The latter number ranks third behind China (about 140,000) and the U.S. (about 80,000). When examining the increase in published papers over the past ten years, Japan's advancement lags well behind that of the U.S. and countries in Europe and Asia, which could be a cause for concern.

A comparison of international trends in R&D shows that Japan still keeps a high level in all areas of basic researches. One can see a direct correlation between the research in each field and the activity of the corresponding industrial field, such as Japan's high industrial technology capability in applications for the environment and energy and its low capability in applications for health and medical care and electronics. The U.S. demonstrates strength in all fields, from basic to applied research and in industrial technology capabilities. The U.S. has a powerful national support system in place, particularly for biological fields, with a distinctive ability to promptly link achievements in basic research to industrial applications. When compared to Europe, Japan leads individual countries in numerous technological fields, but is overtaken by the collective strength of the EU as a whole. Europe's major R&D centers, such as IMEC in Belgium and Fraunhofer Institutes in Germany, are actively engaged in R&D, from basic research to practical development on sensor devices and MEMS. While China and South Korea are blessed with extremely talented researchers, at present their overall capabilities in R&D are still inferior to Japan, Europe, and the U.S. However, these nations have shown superiority in some areas and it appears that the gap in several fields is steadily shrinking. South Korea, in particular, has reached a level of technological capability surpassing Japan, Europe, and the US in such fields as spintronics (STT-MRAM) and organic electronics (displays), largely owing to deep commitment of Samsung Group.

The countries/regions that have published the most papers overall on nanotechnology and materials since 2011 are, in order, China, Europe, U.S., and Japan. Most conspicuous among this trend is the rapid increase in papers coming from China, as they have published nearly twice as many as U.S. The number of research papers published in Japan slightly increased up until 2009, but since then has remained in the same level or on a declining trend. Japan as a whole has been active in applying for patents, particularly on fuel cells and power electronics. However, as should be expected, China has also shown a remarkable increase in this area.

Over the last two or three years, R&D on organic-inorganic hybrid perovskite solar cells, organs-on-chips, trillion sensors, quantum computers, atomically thin two-dimensional functional films (e.g., graphene), topological insulators, and MOFs (metal-organic frameworks) among other topics have been attracting worldwide attention. Since 2000 Japan has steadily produced technological achievements that have drawn attention around the globe, including the discovery of iron-based superconductors, the development of MOFs, and the development of perovskite solar cells. All of these achievements were made in the midst of heated competition.

This type of global, intensely-competitive R&D has further increased the need to speed up development. Efforts to establish an open innovation model at centralized research hubs are being carried out around the world in order to share in the costs of technological development, reduce risk, gather diverse groups of specialists at centralized research hubs, and enjoy the advantages of shared infrastructure, public investment and support for the development of basic and core technologies, and the mutual use of intellectual property. Extra-large research complexes for industry, academia, and government are being established overseas one after another, including Albany NanoTech (USA), IMEC (Belgium), MINATEC (France), Fusionopolis (Singapore), and Nanopolis Suzhou (China). These research complexes are developing their activities on a global scale. In Japan, the Tsukuba Innovation Arena - Nanotech (TIA-nano) is currently expanding its funding and the numbers of participating researchers and research projects.

Countries such as the U.S. and South Korea are working to establish a research network for the shared use of advanced equipment that can be beneficial for the integration of different research fields, collaboration among industry and academia, and development of human resources in order to maximize cost-effectiveness. Japan is also earnestly developing the Nanotechnology Platform for the shared use of state-of-the-art research equipment in the fields of nanofabrication, nanostructural analysis, and molecule and material synthesis. Japan, however, faces a shortage of specialized personnel capable of supporting users of facilities, equipment, and software and engaging in the accumulation and advancement of skills, as well as the necessity of putting in place career paths for such personnel. Any of Japan's industry, academia, or government sectors have not yet found any policies that are adequate for securing and fostering the personnel in the long term and a stable manner.

In addition to these issues, there are several other problems in Japan, including approaches to bridging basic bionanotechnology research to clinical applications, strategies for handling intellectual property in university research and in collaborative research between industry and academia, strategies for promoting standardization in nanotechnology, and risk assessment regarding environmental, health and safety (EHS) issues as well as ethical, legal, societal implications (ELSI), and social acceptance. Regulations and government approvals and licenses relevant to these issues should also be addressed.

Based on the recent trends in the field of nanotechnology and materials described above, Japan is considered to be one of today's world leaders in these fields. However, it remains to be seen whether Japan can maintain its current position with the rise of China, South Korea, and other countries when comparing aspects of each country's R&D policies and strategies and considering the declining shares in Japan's electronics products, as well as Japan's stagnant growth in the development of human resources and the numbers of published research papers and submitted patent applications. Clearly Japan should establish closer collaboration among industry, academia, and government and conduct autonomous actions to strengthen its R&D capabilities.

Considering social expectations in the global scale as well as recent trends in R&D, the following are some Grand Challenges that Japan can aim for in R&D.

- Environmental pollutant removal, more energy-efficient separation in chemical processes, separation and storage of hydrogen for the coming "hydrogen society," and functional materials with separation/adsorption capabilities for medical care and numerous other fields along with their system applications
- Interactive biointerfaces that enable favorable interactions between cells or biological materials and diagnostic and treatment devices at the molecular level by designing more sophisticated interfaces between artificial devices and living organisms
- In electronics, establishment of control technologies for nanoscale heat (phonons), and evolvement of these technologies through integrating different quanta such as electrons, spins, photons, and phonons
- Wearable and implantable electronic devices for healthcare and the augmentation of mind and human's ability, realized by integration of nanoelectronics functions such as sensing, networking, and energy harvesting, on ultra-small, low-cost semiconductor chips
- Formulation of bio-inspired manufacturing technologies by studying the structures and functions of living organisms and incorporating this knowledge in advanced manufacturing technologies represented by computer-aided design and 3D modeling
- Data-driven approaches for high-throughput search and design of materials with higher performance, higher reliability, and lower cost consisting of complex and multi-element system

It is vital for Japan to maintain and strengthen its R&D capabilities in the field of nanotechnology and materials, whether as a source of industrial competitiveness or for the measures of addressing global issues. To this end, Japan should create a scheme of nanotechnology research and development for a new age that will enable to maintain the world's highest level of base technologies and will allow both academia and industry always access to them, and will derive technological innovation leading to practical applications, system integration, and industrialization. In addition to supercomputers for high-speed simulations and a nanotechnology platform for enabling the measurement, characterization, nanofabrication, and synthesis of materials, Japan should build a material information infrastructure to manage vast quantities of material data and to provide them to users on demands. Then Japan should construct a nationwide triangular Nanotechnology and Materials Innovation Platform using these three components to form regional research centers that closely collaborate in their activities. This is the most important message of this report. The Nanotechnology and Materials Innovation Platform should be constructed together with establishment of satellite research centers in various regions of Japan which allow their network to spread its roots throughout the country. Such a platform would allow researchers in any region of Japan access to advanced technologies in other parts of the country, which could help revitalize regional industry. It would also facilitate networking and collaboration among researchers and enable Japan's researchers to collaborate with and compete with the rest of the world.

Contents

1. Purpose and Structure of This Report

1.1 Purpose

The Center for Research and Development Strategy (CRDS) of JST strives persistently to advance science and technology (S&T) toward fulfilment of social needs and realization of our vision of future society. The missions of CRDS are to: 1) Promote dialogues between S&T policymakers, academia, industries, etc., 2) Survey S&T fields and draw their "Panoramic view reports", 3) Select important R&D subjects to be funded by the Government, and investigate effective methods for performing R&D on the selected subjects, 4) Compare the technology levels of Japan with those of other countries, and 5) Propose R&D strategies that can contribute to realization of our vision of future society, enrichment of S&T base, and expansion of research frontier.

This Overview Report is an intellectual asset produced with the aim to widely share information in the field of nanotechnology and materials with stakeholders in S&T. It provides researchers information not only on their own area, but also on the state of the art in areas outside of their expertise, which leads them to explore the possibility of interdisciplinary collaboration. It is also hoped that the report will be utilized by politicians, government officials, businesspeople, teachers, and students who want to gain a deep understanding of trends in relevant fields.

1.2 Structure

Chapter 2 entitled "Overview of the Field of Nanotechnology and Materials" shows how the CRDS generally views the field and characterizes its structure. The chapter defines the domain of the CRDS's activities and describes its approaches. The chapter also provides, from several perspectives, clear overall pictures of the history, current state, and future direction of relevant fields.

2. Overview of the Field of Nanotechnology and Materials

The field of "nanotechnology and materials" is an engine of innovation, bringing innovative technologies to various other fields including the environment; energy; health and medical care; social infrastructure; and information, communications, and electronics. Also, society's expectations toward the field are high as it has potential as fundamental technologies that will lead various industries into the future. This report provides an overview of the field of nanotechnology and materials, covering facts observed around the world including technological advances, national plans and investment strategies, and research potentials. Based on this overview as well as on the social expectations and trends in R&D at the global level, this report refers to future issues to be solved and directions to which the R&D strategies should be oriented.

2.1 Scope and Structure of Nanotechnology and Materials

2.1.1 Definition and Characteristics

Definition and Characteristics of Nanotechnology

In this report, the term "nanotechnology" is defined as follows.

Nanotechnology

An academic or technological field to fabricate and materials at 1 to 100 nanometers dimensions; to create new knowledge and functionality by observing, understanding, and controlling various relevant phenomena of its bulk, surface, and interface structures at atomic or molecular levels; and applying or combining these factors with other knowledge and technology.

Since any academic fields to which the above definition is applied may be blended to form nanotechnology, integration among different fields is the most important characteristic of nanotechnology, by which new technological fields can emerge. To be more precise, the academic aspect of the field should be called nanoscience and the technological aspect should be called nanotechnology. In general, however, they are often lumped together to be called nanotechnology, as is done in this report.

Examples of created nanostructures that fit this definition include ultrafine particles of metals and semiconductors; supermolecules such as rotaxane; materials that make use of nanospaces and nanopores, such as zeolites; and C_{60} (buckminsterfullerene), carbon nanotubes (CNTs), and graphene which have zero-, one-, two-dimensional carbon nanostructures, respectively. In biology, cells have various nanostructures, and cellular functions emerge from such nanostructures and from complex interactions among nanostructures.

The most important characteristics of nanoscale structures of materials include (1) quantum phenomena brought by the size effect, (2) quantum wave properties generated by the repetition of unit cells of a nanolattice, each of which is roughly 10 to 100 times larger than an atom, and (3) nanoscale surface/interface effect generated by an increase in the ratio of the number of atoms at the surface/interface of a material to that of atoms inside the material. These factors lead to nanoscale physical properties that completely differ from ordinarily observed physical properties. Examples include various catalytic effects, as well as electronic, magnetic, optical, mechanical, and thermal properties that can be controlled free from material constants in bulk states. As for the future, attention will be paid to various transport phenomena involving electrons, ions, and molecules confined in nanospaces or nanopores designed and incorporated into materials. Techniques to realize and control such phenomena are expected to become essential in the areas of the environment and energy.

Definition and Characteristics of Materials

In this report, we define materials as matters that possess some useful functions, and materials technology as engineering the functions for applications based on materials science. Materials used in industries can be divided into the following four categories according to their raw materials.

1. Metallic materials: metals such as steel and aluminum; alloys such as stainless steel; amorphous alloys; metallic glass

2. Inorganic materials: ceramics and glass; nonmetallic elements; compounds of nonmetallic and metallic elements, including semiconductors and dielectrics.

3. Organic materials: materials consisting of carbon as the main element as well as oxygen, hydrogen, nitrogen, etc. Examples include macromolecular substances (mainly plastics), electronic materials like organic electroluminescent materials, and supramolecular assemblies and gels that employ self-assembly properties.

4. Biological materials: materials which construct organisms. Main examples include proteins, nucleic acids, and carbohydrate chains.

Materials technology continues to evolve today, supported by various technologies such as texture control at nanoscale dimensions, high-precision measurement at sub-nanometer levels using high-resolution electron microscopes and scanning probe microscopes, predictions of structure and functionality based on ab-initio calculations of electronic structures, and simulation-based analyses.

2.1.2 Nanotechnology and Materials: Social Expectations and Issues Concerning Realization of Technologies

The field of nanotechnology and materials has a role to provide fundamental technologies to be used in a wide range of application fields including the environment and energy; health and medical care; information, communications and electronics; and manufacturing, and contributes to technological innovation through integration with these applied fields. In the following are discussed future prospects and relevant technical issues of these applied fields.

The Environment and Energy

The situation surrounding the world's energy supply has significantly changed since around 2010. One of the factors behind this change is the shale gas revolution that started in the United States. Hydraulic fracturing technology was developed that enabled commercial extraction of large amounts of underground shale gas, which had previously been inaccessible. Due to this technology, the possible production of natural gas is expected to last for several hundred years. With its large underground reserves and cutting-edge technology, the United States has become the largest producer of natural gas in the world. Consequently, the situation surrounding the world's natural gas supply is significantly changing. At the same time, it has been pointed out that the method used to extract shale gas causes water pollution and earthquakes. With many issues to be resolved, the future of shale gas extraction cannot be predicted simply.

The accident at the Fukushima Daiichi Nuclear Power Plant in 2011 was a turning point, and countries all over the world have reexamined their use of nuclear power since then. The accident cast doubt on the safety of nuclear power generation. Germany, Austria, Italy, and Switzerland made national decisions to shift away from nuclear power and have more plans to use more renewable energy than they previously had. In Japan, the operation of all nuclear reactors was suspended after the nuclear accident, whereas about 50 nuclear reactors had been in operation before the accident. As of 2014, none of them has resumed operation. It is thus no longer possible for Japan to have much reliance on nuclear power generation, which once accounted for one-third of the country's total energy production. The International Atomic Energy Agency predicted in September 2012 that the share of nuclear power out of total electricity generation worldwide in 2050 would decrease to 5.0% (less than half of the share for 2011).

At the same time, greenhouse gas emissions are steadily increasing through the massive consumption of fossil fuels such as petroleum, coal, and natural gas as energy sources, and global warming is certainly worsening. If the situation is not resolved, it will give rise to global climate change, frequent natural disasters, and devastating crises affecting food and water supplies, and signs of these problems are already being observed. This ominous scenario is easily extrapolated from the fact that not only advanced countries but also BRICS (Brazil, Russia, India, China, and South Africa), other emerging countries, and developing countries continue, without exception, to drive themselves toward economic development and market expansion. The issue of reducing greenhouse gases faces the entire globe and requires immediate responses. A related global issue is conservation of biodiversity. These issues have a significant effect on human activities.

Lacking fossil fuel resources, Japan once had increased its rate of self-sufficiency in electric power by raising its dependency on nuclear power generation and achieved stable economic development based on this energy strategy. Japan also expected much from nuclear power generation in terms of achieving increasing demanded reductions in greenhouse gas emissions. Because of the nuclear accident, there have been calls to reexamine Japan's energy policy, and the country needs to propose an optimal energy mix according to progress made in energy-related technologies.

Health and Medical Care

People want to lead healthy lives with safety and peace of mind. Meeting this shared desire for quality of life (QOL) is a pressing issue for societies with populations that are rapidly aging due to increased longevity and low birth rates. Ahead of other countries, Japan is now entering the era of a super-aged society.

Maintaining health requires technologies for early detection and prediction of physical abnormalities and prevention of epidemics of infectious diseases. With respect to diagnosing and treating diseases, R&D has been conducted to improve the efficacy of medical interventions. Examples include R&D related to personalized medicine based on a patient's unique genetic background and unification of diagnosis and treatment. Wide adoption of such advances in the clinical setting requires collaboration and integration among a wide range of technological fields. Also, improvement in QOL of patients requires development of technologies for minimally invasive or non-invasive diagnosis and treatment. In the area of regenerative medicine, to which further advance is expected, there is a demand for establishing technologies to culture and process cells as materials depending on the therapeutic purposes.

Information, Communications, Electronics, and Manufacturing

In the area of information and communications, improvements are being made in the performance of computing systems and the capacity of networks. The world is entering an era in which it is possible to provide individuals with needed information at the required time through the collection, accumulation, and high-speed processing of big data. In particular, realization of the IoT (Internet of Things)-based society requires super-microchips equipped with various sensor devices, wireless functionality, as well as an energy-harvesting technology that enables power supply to chips anywhere.

At the same time, advances in information technology that take advantage of big data are expected to have a significant effect on the development in nanotechnology and materials. Massive data sets on materials that are updated and receive new entries on a daily basis enable the detection of new information about materials and the efficient exploration and development of materials with desired properties. There are strong expectations for this new approach to the development of materials, which is called data-driven material design (materials informatics). Also, recent improvements in computer performance have significantly expanded the possibilities of simulation technology. Together with the aforementioned technical progress in data science, increased computer performance is expected to lead to innovations in manufacturing technologies as it makes it possible to create new materials and processes and to introduce new design methods.

2.1.3 Panoramic View on the Field of Nanotechnology and Materials

The field of nanotechnology and materials is founded on nanoscience, which has advanced as a science dealing with nanoscale phenomena based on basic sciences including materials science, optics, the life sciences, information science, and the mathematical sciences. On the basis of nanoscience common fundamental technologies are built and applied to materials in a concrete manner, which enable development of various devices and components, which acts as an innovation engine for innovations in various fields such as the environment; energy; health and medical care; social infrastructure; and information, communications, and electronics. Figure 1 provides a panoramic view of the field.

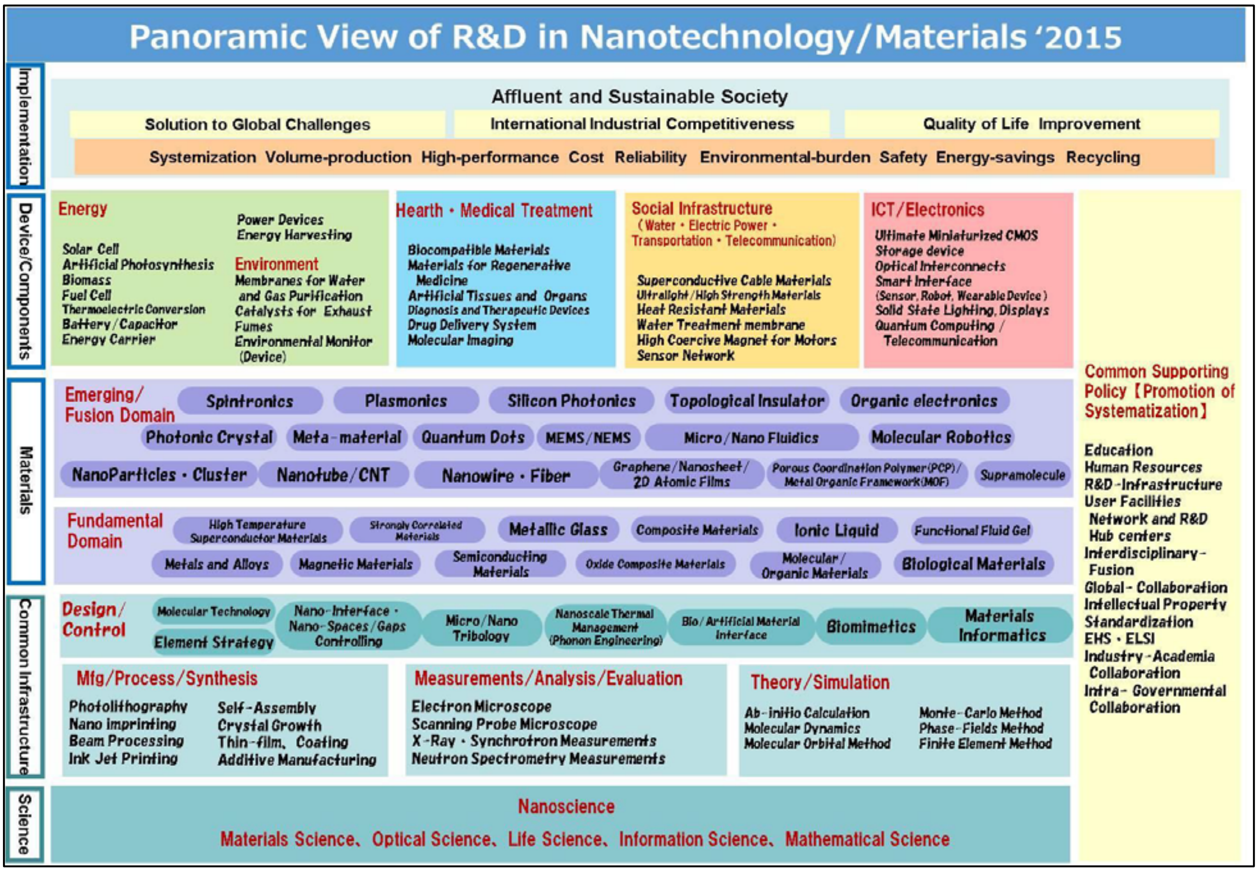


Figure 1

As shown in the bottom layer of the panoramic view, nanoscience is based on combined bodies of knowledge related to nanoscale phenomena studied in materials science, information science, the life sciences, optics, and the mathematical sciences. The common foundation layer consists of not only technologies associated with manufacturing, processing, synthesis, measurement, analysis, and evaluation, but also theory and simulation. The layer representing design and control contains distinctive concepts related to nanotechnology and materials as a whole, such as molecular technologies, interface and space control, and informatics. The common foundation is applied to materials in a concrete manner. The layer representing materials consists of a fundamental domain, which includes basic materials used in nanotechnology and materials, and an emerging integrative domain, which includes composite, hierarchical, and functional materials that are particular to an emerging nanotechnology.

Devices and components are built by combining different materials. Various devices and components are divided into areas as follows: the environment and energy; health and medical care; social infrastructure; and information, communications, and electronics. In this figure, for devices and components that belong to multiple areas, each of them is listed under the area that best represents it. The area of social infrastructure (water, electric power, transportation, and telecommunications) naturally overlaps with the areas of energy and information and communications. Items with greater importance as a system are listed under social infrastructure.

Devices and components are ultimately built into systems, and judgments are made whether the market or society can accept such systems, with consideration given not only to product performance, mass production, cost competitiveness, reliability, and safety, but also to negative environmental impacts, energy saving, and recycling. Only after these issues have been satisfactorily addressed, systems are introduced into society and contribute to achieving goals such as solving global problems, increasing international industrial competitiveness, and improving our QOL

In addition, the right column in the figure (“Common Support Policies”) lists common policy issues such as measures for promoting integration and collaboration, infrastructure improvement, EHS (the environment, health, and safety), and ELSI (ethical, legal, and social issues), all of which are important in the research and development of technologies.

2.2 History, Current State, and Future Direction of the Field

2.2.1 Historical Transition of the Field

Evolution of Materials

The emergence of various new materials including metals, plastics, ceramics, and semiconductors has brought changes to society. Steel and other structural materials supported the Industrial Revolution of the eighteenth century, and lightweight alloys like duralumin contributed to the coming of the era of aviation. The invention of nylon caused a revolution in people’s daily life, especially in the field of apparel. Semiconductors and other electronic materials brought dramatic progress in the area of information and communications. It can be said that “science and technology of materials” have pioneered a new era by creating materials with new functions and dramatic performance gains. Thanks to an active promotion of materials researches, Japan has often led the world in the development of new materials researches, which supported key industries in component production, and created new industries. In the following we show some examples of Japan’s contributions to advances in materials looking back the past.

In 1968, Kenichi Honda and Akira Fujishima (the University of Tokyo at that time) discovered a photocatalytic process, so-called Honda-Fujishima effect, which was then transferred to applied researches, which led to development of a weather-resistant, stain-free self-cleaning technology (photocatalytic coating) and created a 100 billion yen industry through the decades. The discovery of Honda and Fujishima also evolved into a challenge of basic researches aimed at developing artificial photosynthesis, an ultimate clean energy technology.

In 1980, John B. Goodenough and Koichi Mizushima (the University of Oxford at that time) proposed cells using lithium transition metal oxide, which absorbs lithium ions, as the cathode materials. In the 1980s, Akira Yoshino (Asahi Kasei at that time) devised a basic structure with a combination of carbon for the anode and $LiCoO_2$ for the cathode— a prototype of today's lithium-ion batteries and fabricated a practical model in 1986. Lithium-ion batteries were put into practical use in 1991 and later became suitable for wide adoption in portable electronic devices like notebook computers and cellular phones. Subsequently, upsizing of lithium-ion batteries has preceded, which accelerated research and development to use them for HVs (hybrid vehicles) and EVs (electric vehicles).

In 1917, Kotaro Honda (Tohoku University) became the first person to develop a KS steel permanent magnet using an artificially synthesized alloy. The neodymium magnet (correctly speaking $Nd_2Fe_{14}B$), which is considered to be the strongest permanent magnet, was invented in 1984 by Masato Sagawa of Sumitomo Special Metals (presently Hitachi Metals). After a series of subsequent improvements, neodymium magnets are used in various areas such as motors for HV and EV, wind power generators, HDD (hard disks drives), and MRI (magnetic resonance imaging). The production volume of neodymium magnets has rapidly increased year by year. For sintered products, the worldwide production volume has already reached 80,000 tons per year.

In 1986, Isamu Akasaki (Nagoya University at that time) and Hiroshi Amano (Nagoya University) achieved successful results in the growth of a high-quality single-crystalline film of gallium nitride. In 1993, Shuji Nakamura (Nichia at that time) developed a high-luminosity blue light-emitting diode (LED) using indium gallium nitride (InGaN), which led to practical applications. Subsequently, in 1996, blue LEDs and blue lasers making use of quantum well structures were put to practical use for the first time. By combining the blue LED with a phosphor white LEDs were realized and came into widespread use, which has spread to LCD backlights, high-efficiency lightings, and vehicle headlights. Akasaki, Amano, and Nakamura jointly received the Nobel Prize in Physics in 2014 for their invention of the blue LED, which enabled creation of high-luminosity, energy-saving white light sources.

Concerning the magnetic heads of HDD (hard disk drive) capable of high-density recording and high-speed reading of information, Terunobu Miyazaki (Tohoku University) developed a TMR (tunnel magnetoresistive) device (AlOx was used as the material for the tunnel barrier) with a magnetoresistance ratio as large as 20% at room temperature. In 2004, Shinji Yuasa and colleagues at the National Institute of Advanced Industrial Science and Technology (AIST) achieved a significant improvement in the TMR ratio reaching as high as 200 % by using magnesium oxide for the tunnel barrier of the TMR device. The technology was put to practical use in 2007 and is currently used in the magnetic head of high-capacity HDDs, as well as to development of magnetic random access memories (MRAM) with remarkable high-density integration.

The transparent amorphous oxide semiconductor (TAOS), which was discovered by Hideo Hosono (Tokyo Institute of Technology) and colleagues in 1994, is a transparent oxide semiconductor that has high electron mobility even in the amorphous phase. In 2004, they used InGaZnO (IGZO), one type of the TAOS, and demonstrated that it can be successfully used in a thin-film transistor (TFT) that realizes low power consumption. The technology is currently being incorporated into the displays of smartphones and other products.

Japan's significant contribution also extends to carbon nanomaterials, which have characteristic nanoscale structures. One example is the fullerene C_{60}, which was discovered in 1984 by Harold Kroto (UK), Richard Smalley (US), and Robert Curl (US). Already in 1970, Eiji Osawa (then of Hokkaido University) proposed a model of a soccer ball structure made up of six- and five-membered rings of carbon. In 1991, Sumio Iijima (NEC at that time) discovered a carbon nano tube (CNT), which is a typical carbon nanomaterial, and proposed a model of a tubular structure with a network of six-membered rings of carbon. Subsequently, Morinobu Endo (Shinshu University), who had studied carbon fibers since the 1970s, developed a technique to grow CNTs by a vapor phase method and extended it to a mass production technology. Carbon nanomaterials including graphene, which emerged in 2004, have peculiar electrical, mechanical, and chemical properties and are attracting strong expectations for engineering applications in areas such as electronic devices, supercapacitors, displays, tough composite materials, as well as medical and biological applications. As described before, Japan has made a considerable contribution to the area.

Figure 2 shows main examples of socially and economically important materials research that was done in Japan.

Social & Economic Impact brought by Materials Researches

Permanent Magnet
K. Honda (World First Synthetic Magnet@1917)
M. Sagawa (World Strongest Magnet@1984)
→Motor, Electric Vehicle, Windmill, HDD

Superconductor (SC) Materials
H. Maeda (Bi-based110K-HTSC, HTSC Cable@1988)
J. Akimitsu (Metal-based40K-SC@2000)
H. Hosono (Iron-based32K-HTSC@2008)
→HTSC wire materials、Ultrahigh field NMR

Carbon Nano Tube (CNT)
S. Iijima (Discover of CNT@1991)
M. Endo (Mass synthesis of CNT@1988)
→Electrode of Li-ion Battery、Touch-Panel

Spintronics
S. Iwasaki (Perpendicular Magnetic Recording@1977)
T. Miyazaki (Room temperature operation of TMR@1995)
S. Yuasa (Giant TMR by MgO tunnel barrier @2004)
→Ultra-high density HDD, MRAM

Photocatalyst
K. Honda, A. Fujishima (TiO_2 Photocatalyst@1968)
→Photocatalyst coating, Environmental Cleaning
(@1994 by K. Hashimoto)

Catalyst (Organic Synthesis)
E. Negishi, A. Suzuki (Cross-coupling reaction@1970s)
R. Noyori (Asymmetric Synthesis@1986)
→Drugs, Agrochemicals, fragrance, Amino Acid

Blue LED, LD
I. Akasaki, H. Amano (GaN single crystal、p-type doping @1989)
S. Nakamura (High-brightness blue LED, LD@1993)
→LED illumination, backlight of LCD, Traffic signals

Oxide Materials
H. Hosono (IGZO TFT, operation@2004)
→TCO, Driver TFT for LCD・OLED

In addition, Li-ion Battery (A. Yoshino) @1983 、Er-doped Fiber Amplifier (M. Nakazawa) @1989 etc.
Nobel Prize; Ten Laureates in Physics, and seven in chemistry

Figure 2

In many cases, elements characterized by a small amount of reserves and a limited number of producing countries, such as rare earth elements and rare metal elements, are key materials determining the performance, function, and cost of electronic parts, catalytic materials, and magnetic materials, all of which have a significant importance in Japanese industry. As China announced its resource protection plan in 2006, the need to reduce the use of these materials and find substitutes attracted attention and became an urgent issue. In the following year, the Ministry of Education, Culture, Sports, Science and Technology (MEXT) and the Ministry of Economy, Trade and Industry (METI) started the Elements Strategy Project (an industry-academia-government collaboration) and the Project for Developing Substitutive Materials for Rare Metals, respectively, as joint projects for significant collaboration among government agencies. In 2012, a large-scale project, the Elements Strategy Project (for Creating Research Centers), was newly started.

In general, it takes a long time (usually 15 to 30 years) from discovery to commercialization of materials. This proceeds through intermediate steps like developing applied technologies, creating prototypes, securing reliability, and developing mass production techniques. In recent years, European countries and the United States have actively made efforts to establish the field of informatics, a new approach to efficient exploration of new materials and material design. The purpose of the field is to enable new discoveries regarding materials and to bring innovations to the field of materials science by improving large-scale databases on materials and making full use of rapidly advancing computational science and information science. In the United States, a national project called the Materials Genome Initiative was started and investments that amount to about

10 billion yen are made annually. Japan is required to take a strategically urgent action in response to such trends.

Presently there exist high expectations for innovation by materials technology to solve global sustainability issues. For this purpose the role to be played by nanotechnology is significant as the driving technology for such innovation. Based on understanding and control of phenomena in the nanoscale, there is a strong expectation for technological developments that extend such phenomena to mesoscopic and macroscopic scales, as well as development of composite materials that produce new functionality combining functions of elements at a nanoscale level.

Advances in Nanotechnology

The second half of the twentieth century saw a dramatic economic growth owing to advances in science and technology, the forerunner of which would be the emergence of new concept of physics called quantum mechanics. Based on quantum mechanics, significant advancements were made in physics, chemistry, and other academic fields. In particular, after the end of World War II, engineering progressed based on these fields, new technologies were developed, and the semiconductor industry and many other industries flourished.

Among the advanced technological flow as described above, U.S. physicist and Nobel laureate Richard Feynman commented, “There’s plenty of room at the bottom,” which has often been cited as a phrase with the foresight conscious of the nanoscale dimensions. The comment is from a lecture given at an American Physical Society conference in 1959, and predicted the potential of science dealing with phenomena at the atomic or molecular level. Three years later, in 1962, Ryogo Kubo (the University of Tokyo at that time) theoretically calculated the quantum size effect for metal particles and showed that metal particles of the nanoscale dimensions have different physical properties from those of bulk, which was considered the first concrete theoretical prediction on a nano-scale size effect. Other important contributions made by Japanese researchers in the 1960s include the proposal and experiment involving semiconductor superlattices by Reona Esaki (IBM Research in the United States; 1969) who was awarded the Nobel Prize in Physics for his research on tunnel diodes. In 1974, at an international conference on production technologies, Norio Taniguchi (the Tokyo University of Science at that time) proposed a technological concept using the term nanotechnology for the first time.

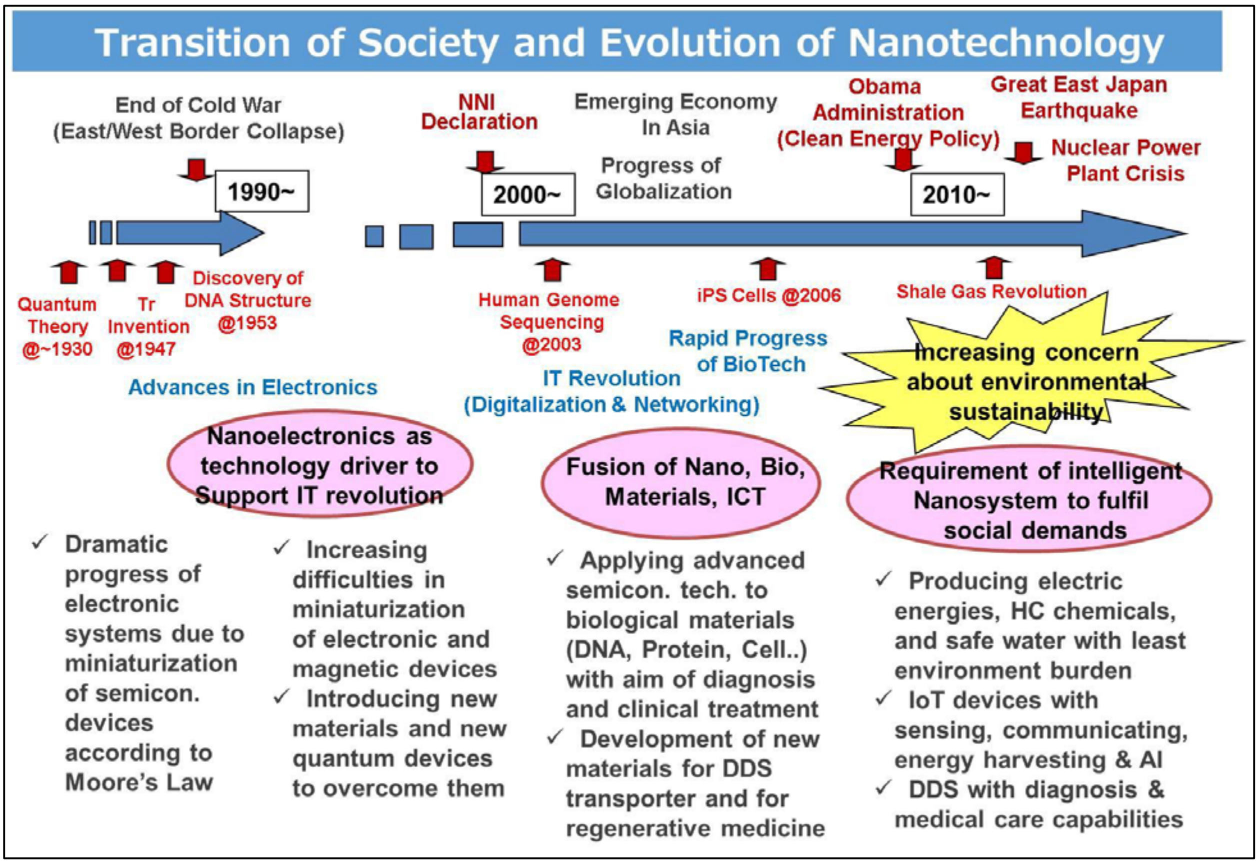


Figure 3

As shown in Fig. 3, as the Cold War era came to an end in the 1990s, U.S. military technologies such as the Global Positioning System and a communication network technology called the ARPANET (Advanced Research Projects Agency Network) were made available for civilian use. The ARPANET evolved into the Internet and started to have a profound impact on people's lives. Due to advances made in the aforementioned technology for miniaturization of semiconductor devices, digitization of electronic devices and information networks evolving around the Internet led the subsequent IT (Information Technology) revolution.

Starting in the second half of the 1990s, a limit to miniaturization of semiconductor devices became apparent, which gave rise to demand for technological innovations that would overcome the limit. Technological innovations were also constantly pursued as advances were made in the data storage industry (producing hard disks and other devices) in terms of miniaturization of recorded domains and increases in storage capacity and as these advances occurred at a speed greater than the pace predicted by Moore's law for semiconductors. These situations drove R&D in nanotechnology, and the central theme of research at that time was nanoelectronics for the IT revolution.

In 2000, U.S. President Bill Clinton announced the National Nanotechnology Initiative (NNI). The United States was ahead of other countries in areas like information and communications technology, software technology, and biotechnology, all of which supported the IT revolution at that time. In terms of industries producing advanced technologies for the twenty-first century, attention was being paid to the importance of nanoscale manufacturing technologies backed by materials science. Carbon nanotubes and GaN blue LEDs had already been developed in Japan as new technologies based on materials science. The announcement of the NNI in US reflected the strong concern of the country and its intention to lead the world in R&D competition in nanotechnology based on materials science in order to maintain the country's economic and military dominance in the twenty-first century.

Starting around 2000, dramatic advances in biotechnology became apparent, triggered by the sequencing of the human genome. Progress in the life sciences attracted the interest of researchers in information science and materials science, and many researchers of these fields started to participate in biological R&D. Subsequent advances in the life sciences were remarkable. New discoveries and new technological achievements that could rewrite textbooks, such as creation of induced pluripotent stem (iPS) cells, occurred one after another, which resembled the situation 100 years ago when the field of quantum mechanics began to emerge. Taking into consideration that the materials science, which supports advanced technology industries of today, has been developed based on quantum mechanics, the benefits to humankind of the enormous amount of knowledge accumulated in the life sciences would be immeasurably large. In comparison with the case of quantum mechanics which took as long as 100 years from the emergence to the creation of present industrial success, in the case of life sciences the accumulation of knowledge may flourish in by far the shorter time scale as social and industrial technologies in medical, diagnostic, and health-related fields, since there are strong supporting tools of nanotechnologies in molecular- and atomic-scale measurements, simulations, nanofabrication or materials synthesis which have been advanced based on materials sciences. Most of the technologies, devices, and equipment used to quantify biological information obtained from genes, RNA, protein, metabolites, and the like could not exist without contributions from nanotechnology and materials technology.

Although our lives have dramatically improved over the past 20 years thanks to the IT revolution, we face important fundamental issues concerning the sustainability of human society. These issues include environmental pollution, global warming caused by CO_2 and other greenhouse gases emitted by burning fossil fuels, and depletion of food and natural resources caused by global population growth and economic globalization. Full-fledged efforts from the science and technology community are essential to solving these issues. Particularly, the role of nanotechnology is important as it centers on materials science and produces technological innovations by combining information science and the life sciences.

As described above, the role of nanotechnology has evolved along with technological progress and the demands of the times. The process of this evolution has gone through three stages "Cutting-edge Nano", "Fusion Nano", and "System Nano". As new technologies and new social issues emerge, the process has been repeated, resulting in generational changes occurring in a layered and hierarchical manner.

The first stage in the evolution of nanotechnology is "Cutting-edge Nano", which is in other word the pursuit of ultimate nanoscale functions for component technologies, and requires persistent R&D efforts along with the incorporation of new concepts.

The second stage is "Fusion Nano", which raises integration among different fields through interdisciplinary research on component technologies at the ultimately progressed level and produces new integrative nanotechnologies with new functions. Appropriate techniques are essential for such integration as it requires not only improvement of the performance of individual materials, but also optimization of the component materials aimed at performance enhancement for the device or system as a whole.

The third stage is “System Nano”, which is the stage of evolution in which various nanoscale component technologies or new integrative nanotechnologies based on them are combined. We define the “nanosystem” as a component or an apparatus that provides, as a whole, sophisticated functions to solve important issues by integrating key technologies and materials in the field of nanotechnology, and those in other fields. This is not the concept specific to nanotechnology but is a newly-defined concept concerning the process and result of combining components and realizing useful functions as a system. For further advances, “systematization of nanotechnologies” is important as the final stage in the creation of value.

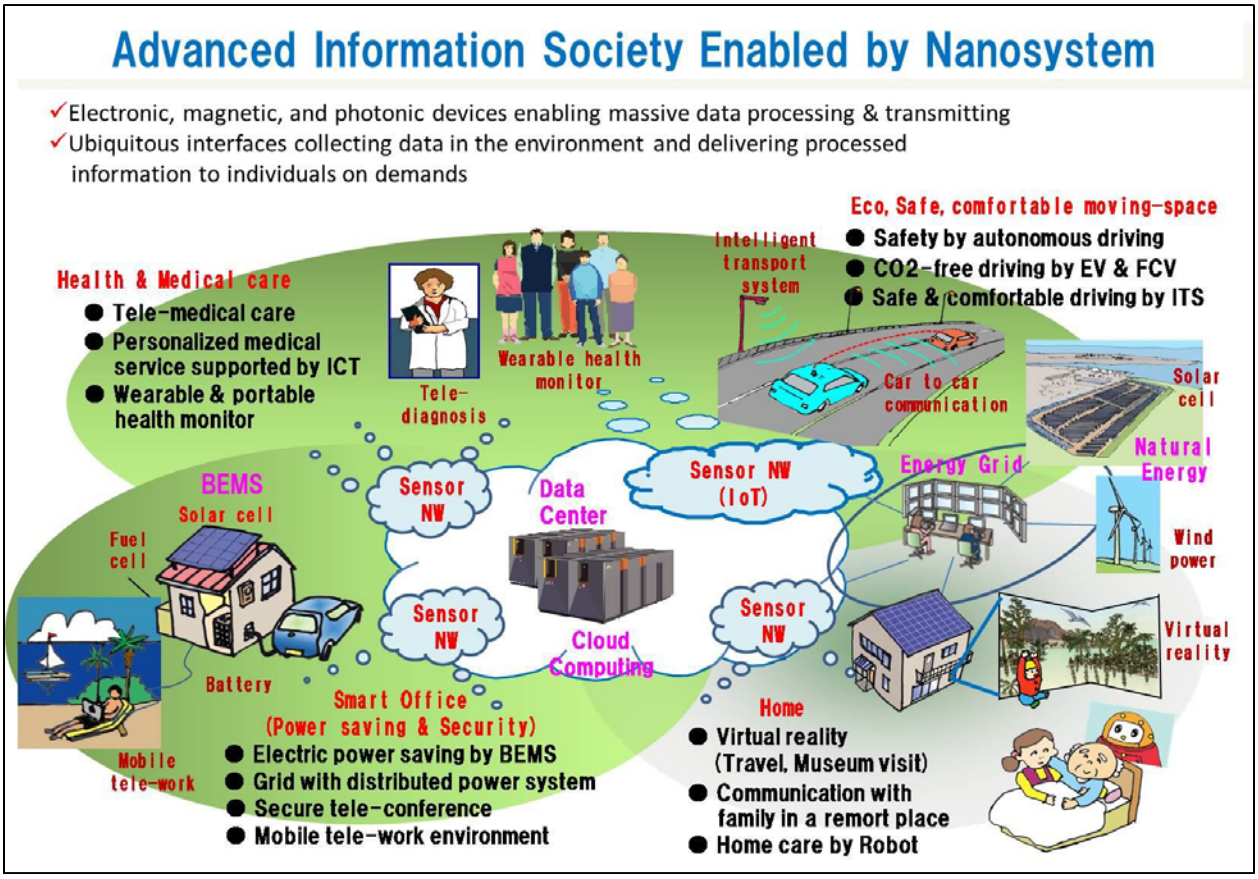


Figure 4

Figure 4 shows an example of nanosystem to enable advanced information society in future. In our surrounding, various sensor devices will be deployed and collect massive data there continuously. Those data are up-loaded to a communication network and transmitted to a high-performance computing system in a data center. New knowledge or information is produced in the data center from the massive data and delivered to individuals on demands through various man-machine interface devices. These services are made possible by the combination of sensor networks, cloud computing system, and ubiquitous interfaces, where nanoelectronic, magnetic, and photonic devices enable massive data processing and transmitting. Thanks to these services, one can enjoy safe, secure and comfortable life at home. It is particularly effective for aged persons or handicapped persons, in the sense that they can enjoy virtual reality experiences, such as travels or museum visits without going there, and communication with family members in a remote place. Smart robots will take care of those peoples and homes when family is out by notifying the situation to an appropriate person when something irregular or abnormal happens. Such robots are composed of sensor devices, actuating devices, batteries, and nanoelectronic processor chips, working together as a nanosystem for robot operation.

In an advanced information society, health condition will be monitored continuously by wearable monitors attached on a body and data collected by the monitor will be transmitted to a medical center. One can receive personalized medical service from a doctor when needed, based on the collected data and personal data stored in the center through a remote communication system. The wearable health monitor is composed of various sensing devices, wireless communication devices, and small batteries with high-energy density or energy-harvesting devices integrated on a sheet-like substrate, working together as a nanosystem for health and medical care.

One can enjoy safe and comfortable driving with small environmental load by CO_2-free electric vehicles or fuel-cell vehicles. The car navigation is supported by the information obtained from the ITS (Intelligent Transport System) and from the car-to-car communication. Thus, autonomous driving becomes possible by sensing surrounding traffic conditions, recognizing the present situation, and controlling the driving. The sensing devices of millimeter or laser radars and 2D image sensors, 3D real-time recognition AI chips, and high-speed memory chips containing 3D road-map data work together as a nanosystem, enabling the autonomous driving.

In the future smart office, electric power consumption will be saved by BEMS (Building Energy Management System), and secure ICT environment ensures tele-conference meetings and tele-works in remote places using mobile terminals. Solar cells installed on a roof, rechargeable batteries to store the energy produced by the solar cells, stationary fuel-cells for a distributed power supply system, and high-efficient power electronic devices work as a nanosystem for energy saving in the office building with BEMS.

2.2.2 Basic Policies of Japan

Outline and Budgets

This section outlines the field of nanotechnology and materials in Japan since 2001, focusing on the country's policies, trends in R&D and commercialization, and the current state of the field.

Basic Policies

After 2000, major countries worldwide started their large-scale national investment strategies concerning nanotechnology; on the other hand, Japan had already been executing national strategies on nanotechnology in a layered manner since the 1980s at the Science and Technology Agency (presently included in MEXT) and the Ministry of International Trade and Industry (MITI). Examples include the Hayashi Ultrafine Particles Project (1981-86) and more than ten other projects were promoted by the Research Development Corporation [JRDC] (today's Japan Science and Technology Agency [JST]) under the Science and Technology Agency as Exploratory Research for Advanced Technology (later as JST Strategic Basic Research Program ERATO) and the Atom Technology Project (for the ultimate manipulation of atoms and molecules; 1992-2002; 26 billion yen for ten years), which was launched as a large-scale project by the New Energy and Industrial Technology Development Organization (NEDO) under MITI. These projects started prior to the construction of the First Basic Plan for Science and Technology (1996) with which the Japanese government began seriously preparing science and technology strategies.

Thanks to the situations described above, Japan could have a relatively smooth start to its national plan for nanotechnology and materials at approximately the same time as the launch of the NNI in the United States. After the establishment of the Council for Science and Technology Policy (CSTP) under the Cabinet Office, the field of nanotechnology and materials was selected as one of four fields for priority promotion in the Second and Third Basic Plans for Science and Technology (2001-05, 2006-2010, respectively) and was prioritized in resource allocation during 10 years along with the life sciences, information and communications, and the environment as shown in Fig. 5.

Despite the fact that these four priority fields have been focused as policy-response challenges, too much emphasis was put on individual promotion strategies for these fields and policies were made independently for each field (The Interim Report of the Special Committee on the Basic Plans of the Council for Science and Technology, December 25, 2009). Some pointed out that the administrative system for overall coordination intended to remove such vertical division did not work satisfactorily, resulting in such a situation that individual strategies did not turn into general strategies, which quite possibly hindered achievement of policy objectives stated in the Third Basic Plan for Science and Technology. The field of nanotechnology and materials was expected to become an overarching, integrative field connecting other fields such as the life sciences, information technologies, and the environment and was therefore important in the execution of strategies.

In the Third Basic Plan (2006-10), important R&D-related issues in the field of nanotechnology and materials were identified for five areas (nanoelectronics; nanobiotechnology and biomaterials; materials; fundamentals promoting the field of nanotechnology and materials; nanoscience and materials science), and these areas were promoted accordingly. Major efforts and results are as follows.

- Upgrading infrastructures such as the X-ray free-electron laser (nationally designated as a critical technology) and the Nanotechnology Network
- Strengthening industry-academia-government collaboration based on the Tsukuba Innovation Arena (TIA-nano), which was the first open innovation center of Japan
- Steady progress in the cross-ministerial projects: the Elements Strategy Project (of MEXT) and the Project for Developing Substitutive Materials for Rare Metals (of METI)

The effects of long-running investment in nanotechnology by the Japanese government are finally showing up in various areas.

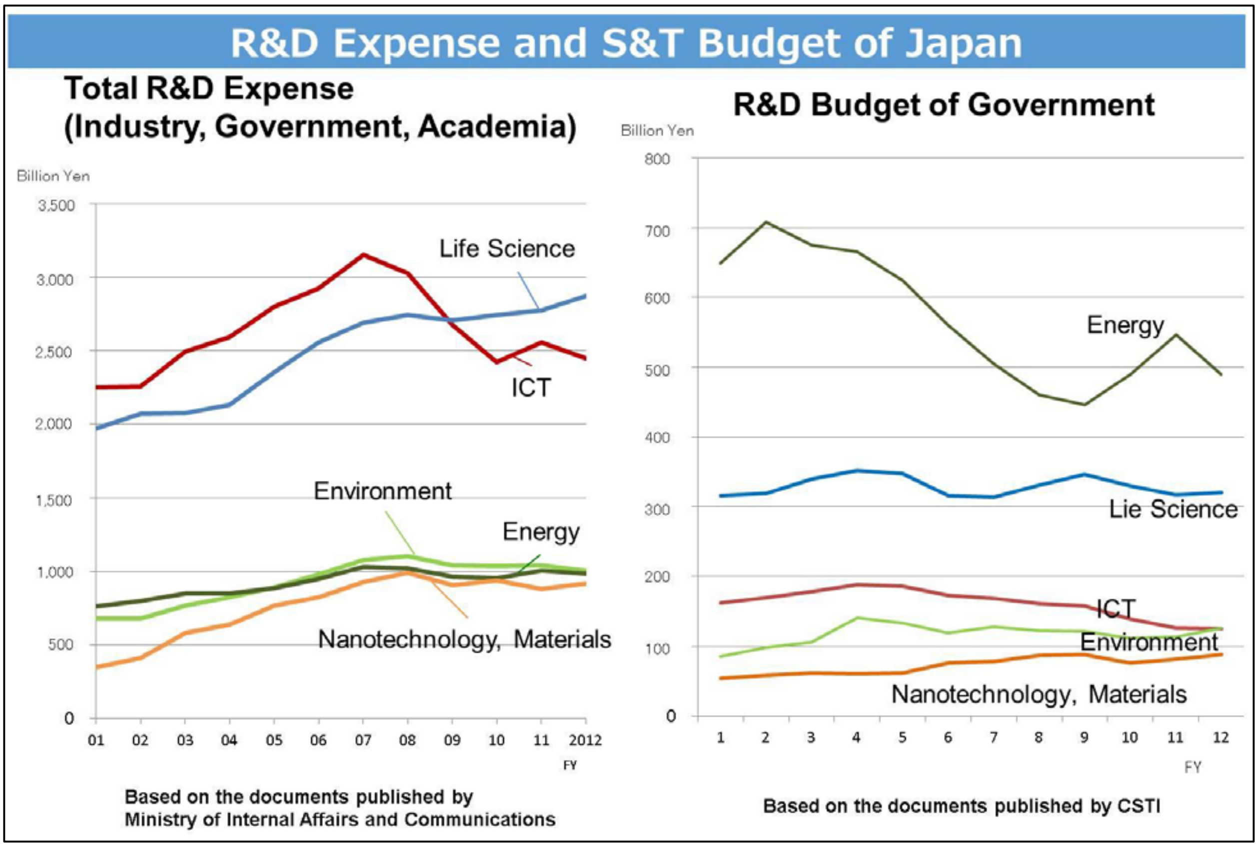


Figure 5

Based on reflections of the precedent plan, the Fourth Basic Plan (2011-15) made a drastic shift from policies promoting prioritized S&T fields ("bottom-up policies") to problem-solving ones to meet the social expectations ("top-down policies"). The field of nanotechnology and materials is therein positioned as an overarching field encompassing three major policy issues, i.e., (1) Reconstruction and regeneration of the east-Japan earthquake disaster, (2) Green innovation, and (3) Life innovation. We evaluate this positioning to be appropriate, taking into account the overarching nature of the field. We should note that the academic and technological networks created through initiatives over the past ten years should not be segmented, since the field of nanotechnology and materials was not set as an independent strategic initiative and separately associated with the three strategic policy issues. Relevant government offices should cooperate with each other and make their efforts in a well-balanced manner, to link policy issues with technological fields that provide solutions and promote the field in whole, maintaining networks among different fields.

It is clearly stated in the General Strategies for Scientific and Technological Innovation for 2014, which were subsequently approved by the Cabinet along with Japan's revitalization strategy, that nanotechnology plays an important role as an overarching technology that can be used to increase industrial competitiveness and solve policy issues. In the Fifth Basic Plan for Science and Technology, we expect further strengthening of the field by the clear positioning of the field of nanotechnology and materials in the system of S&T policies of Japan.

R&D Projects

The following is an overview of major R&D programs and projects in Japan. The aim here is to facilitate understanding of the current trends in the country's R&D policies. The projects discussed are those that the CRDS is aware of and that are related to the field of nanotechnology and materials. According to the categorization of fields used in this report, these projects are divided into different categories such as the environment and energy. (If a project belongs to multiple fields, it is listed under its main field.)

Taking into account basic research and the outcome (i.e., practical application or commercialization), the Council for Science, Technology, and Innovation (CSTI) created under the Cabinet Office implements the R&D programs listed in Figure 6 without being restricted by the boundaries of government agencies and relevant fields.

Cross-ministerial Nanotechnology-related Large Scale R&D Projects of Japan (CSTI)

Strategic Innovation Promotion Program (SIP) (FY2014-)		
Environment Energy	Innovative Combustion Technology	Sugiyama (Toyota)
	Next-Generation Power-electronics	Omori (Mitsubishi Electric)
Social Infra-structures	Technology for Maintenance, renewal and management	Fujino (Yokohama Natl. Univ.)
	Innovative Structural Materials	Kishi (ISMA)
Materials Common Base	Innovative Technology for Design and Production	Sasaki (Hitachi)

Impulsing Paradigm Change through Disruptive Technologies Program (ImPACT) (FY2014-)		
Health Medicine	Ultra high-speed multiplexed sensing system beyond evolution for detection of extremely small amounts of substances	Miyata (Nagoya Univ.)
Social Infra-structure	Reduction and Resource Recycle of High Level Radioactive Wastes with Nuclear Transmutation	Fujita (Toshiba)
Information, Communication and Electronics	Achieving ultimate Green IT Devices with long usage times without charging	Sahashi (Toshiba)
	Advanced Information Society Infrastructure Linking Quantum Artificial Brains in Quantum Network	Yamamoto (NII)
Material, Materials and Common Base	Super High-Function Structural Proteins to Transform the Basic Materials Industry	Suzuki (Kojima Ind.)
	Realizing an Ultra-Thin and Flexible Tough Polymer	Ito (Univ. Tokyo)
	Ubiquitous Power Laser for Achieving a Safe, Secure and Longevity Society	Sano (Toshiba)
	Innovative visualization technology to lead to creation of a new growth industry	Yagi (Canon)

	Funding Program for World-Leading Innovative R&D on Science and Technology (FIRST) (FY2009—FY2013)	
Environment Energy	Innovative SiC Power Electronics Technology Toward Low-Carbon Society	Kimoto (Kyoto Univ.)
	Development of Organic Photovoltaics toward a Low-Carbon Society: Pioneering Next Generation Solar Cell Technologies and Industries via Multi-manufacturer Cooperation	Segawa (Univ. Tokyo)
	Innovative Basic Research Toward Creation of High-performance Battery	Mizuno (Univ. Tokyo)
Health Medicine	System Integration for Industrialization of Regenerative Medicine: Creation of Organ Factory	Okano (TWMU)
	Development of Innovative Diagnostic and Therapeutic Systems Based on Nanobiotechnology	Kataoka (Univ. Tokyo)
	Research and Development of Innovative Nanobiodevices Based on Single-Molecule Analysis -Ultra-fast Single-Molecule-DNA Sequencing, Ultra-Low-Concentration Virus Detection, and Ultra-Sensitive Biomolecule Monitoring-	Kawai (Osaka Univ.)
Information, Communication and Electronics	Challenges for super organic electroluminescence devices through innovation of organic semiconducting materials	Adachi (Kyushu Univ)
	Technology Development for Photonic-Electronic Integration System	Arakawa (Univ. Tokyo)
	Research and development of integrated microsystems	Esashi (Tohoku Univ)
	Research and Development of Ultra-low Power Spintronics-based Logic VLSIs	Ohno (Tohoku Univ)
	Creation of Face-to-Face Communication Industry by Ultra High-Speed Plastic Optical Fiber and Photonics Polymers for High-Resolution and Large-Size Display	Koike (Keio Univ.)
	Development of Core Technologies for Green Nanoelectronics	Yokoyama (AIST)
	Quantum information processing project	Yamamoto (NII)
Material, Materials and Common Base	Quantum Science on Strong Correlation	Tokura (RIKEN)
	Development and Application of Atomic-Resolution Holography Electron Microscope	Osakabe (Hitachi)
	Exploration of New Superconductors and Related Functional Materials and Application of Superconducting Wires for Industry	Hosono (Tokyo Inst. Tech.)

Figure 6

MEXT maintains research centers from the standpoint of promoting world-class research and industry-academia collaboration and creating innovation (Figure 7).

Nanotechnology-Related Research Center Project of Japan (MEXT)

	Center of Innovation (COI) Program (FY2013-)	
Health Medicine	Center for Creation of Motivation–Progressive Society lead by ideal self and family ties by means of realization of casual sensing and day–to–day medical checkups	Toshiba, Tohoku Univ , Nihon Kohden
	Open Innovation Center for Production of Things to lead the transformation to "Smart Life–care Society"	Kawasaki City Industrial Promotion Foundation
	Center of Innovation for Sustainable Life Care, Ageless Society	Univ Tokyo
	Nurture of Super–Japanese and Enhancement of Industrial Competitiveness by means of Activation of Human Power – Construction of an Affluent Society	Panasonic, Osaka Univ
Social Infrastructure	Construction of Next–generation Infrastructure System by Innovative Materials – Realization of "Centuries Society" that can coexist with the Earth in the Safety and Security	Kanazawa Inst Tech
	Aqua Innovation Base to contribute to the Rich Living Environment of the World and Global Sustainability	Hitachi–Infrasystem, Shinshu Univ
ICT	The Last 5X Innovation R&D Center for a Smart, Happy and Resilient Society	Panasonic, Kyoto Univ
	Center of Innovation for Creation of the World's Most Advanced ICT to Support the Smart Society where All Generations can enjoy the On–Demand Life & Work	KDDI Research Lab, Tokyo Inst Tech
Materials Common Base	COI for Creating Co–evolutional Social Systems	Kyushu Univ
	Innovation Center for Coherent Photon Technology	Univ Tokyo

World Premier International Research Center (WPI) Initiative (FY2007-)		
Environment Energy	International Institute for Carbon-Neutral Energy Research(I2CNER), Kyushu University	Sofronis (Kyushu Univ)
Health Medicine	Institute for Integrated Cell-Material Sciences(iCeMS), Kyoto University	Kitagawa (Kyoto Univ)
	Institute of Transformative Bio-Molecules(ITbM)	Itami (Nagoya Univ)
Materials Common Base	International Center for Materials Nanoarchitectonics (MANA)	Aono (NIMS)
	Advanced Institute for Materials Research (AIMR)	Kotani (Tohoku Univ)

Creation of Innovation Centers for Advanced Interdisciplinary Research Areas Program (FY2006-)		
Health Medicine	Information, Communication and Electronics	Okani (TWMU)
Information, Communication and Electronics	COE for Nano Quantum Information Electronics	Arakawa (Univ Tokyo)
	Photonics Advanced Research Center	Kawata (Osaka Univ)
	R&D Center of Excellence for Microsystem Integration Research Initiative	Ono (Tohoku Univ)
	Vertically Integrated Center for Technologies of Optical Routing toward Ideal Energy Savings (VICTORIES)	Namiki (AIST)

Figure 7

MEXT and METI implement theme-specific programs with various goals such as creation of research centers and networks, industry-academia collaboration, and industrialization, which are deemed to deserve government support (Figure 8).

Aiming at strengthening of industrial competitiveness, NEDO promotes the search for technological seeds that will turn into core technologies in future industry, medium- and long-term projects that will form the foundation for industrial competitiveness, and technological development at each stage in practical application development by the wisdom from industry, academia, and the government (Figure 9).

Major National R&D Projects on Nanotechnology and Materials

MEXT ※selected AP Projects

- Elements Strategy Project (Establishment of Research Hubs)
  - Electronic Materials
  - Magnetic Materials
  - Secondary Battery and Catalyst
  - Structural Materials
- Tohoku Innovative Materials Technology Initiatives for Reconstruction
- Environmental technology development program that utilizes nanotechnology
- Nanotechnology Platform
- Photon and Quantum Basic Research Coordinated Development Program
- Photon Frontier Network

METI

- Development of Process Technology for Chemicals Production using Innovative Catalysts
- The Next-Generation Power Electronics Technology Development Project
- Rare Metal Alternative Materials Development Project
- Innovative New Structural Materials Technology Development Project
- Nano-Carbon Material Practical Realization Project

Figure 8

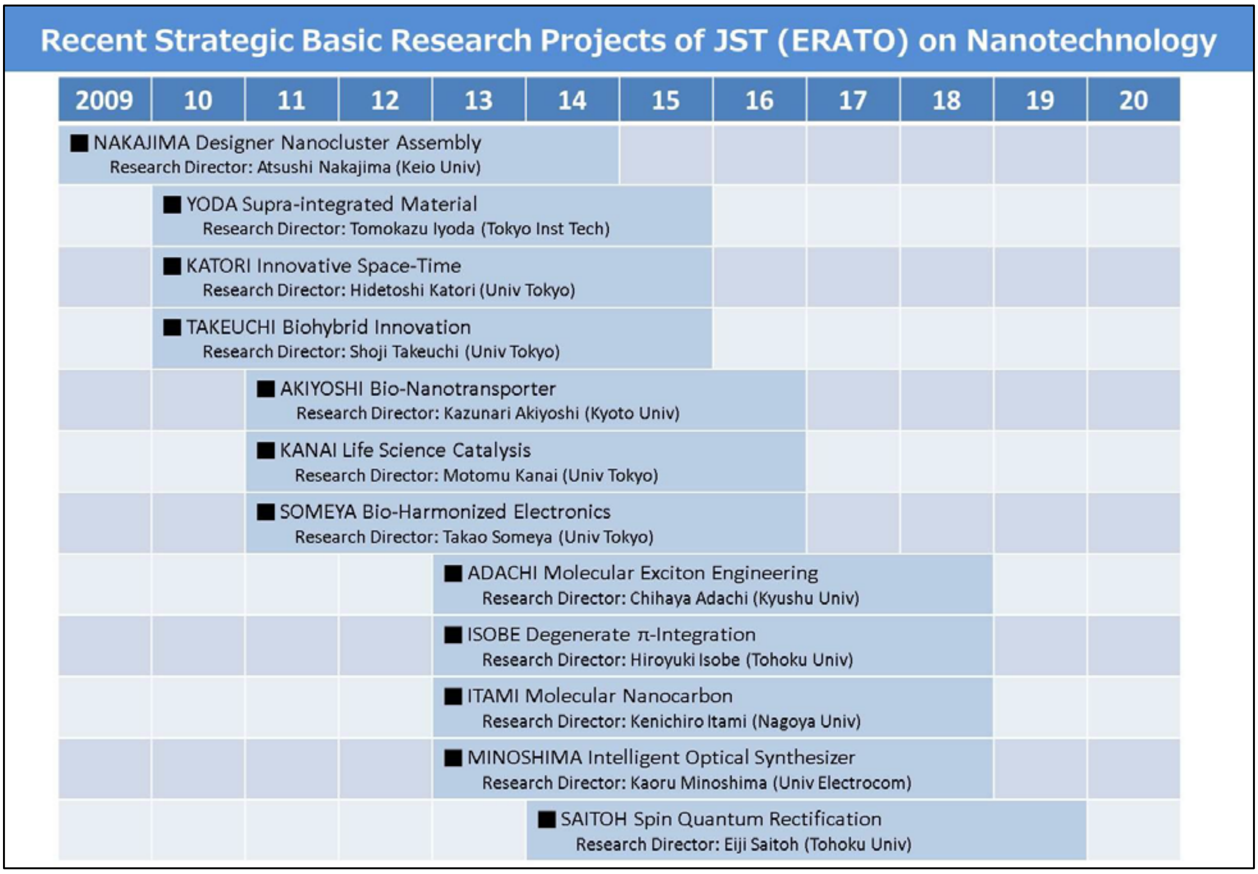
Major NEDO Projects on Nanotechnology and Materials

Photovoltaic Generation	Research and Development of Solar Energy Technology	FY2008 – 14
	Technology Development of Efficiency Improvement and Maintenance and Management of Solar Power Generation System	14 – 18
	Technology Development of Photovoltaic Power Generation Recycle	14 – 18
Fuel Cell and Hydrogen	Development of PEFC Technologies Aiming for Practical Application	10 – 14
	Technology Development of Solid Oxide Fuel Cells (SOFC) for Promotion of Commercialization	13 – 17
	Hydrogen Utilization Technology Development	13 – 17
	Pilot Research and Development of Hydrogen Utilization	14 – 17
Storage Battery	Research and Development Initiative for Scientific Innovation of New Generation Batteries	09 – 15
	Fundamental Study of an Evaluation Method for Battery Material Research and Development	10 – 14
	Applied and Practical LiB Development for Automobile and Multiple Applications	12 – 16
	Fundamental Study of Evaluation Method for Advanced and Innovative Battery Material Research and Development	13 – 17
Powerelectronic	Novel Semiconductor Power Electronics Project for a Low Carbon Emission Society	13 – 18
Catalyst	Development of Fundamental Technologies for Green and Sustainable Chemical Processes	13 – 15
	Technology Development for Basic Chemical Manufacturing Processes to Make Carbon Dioxide Raw Materials	14 – 21
	Technology Development for Functional Organosilicon Chemical Manufacturing Processes	14 – 21
Electronics	Ultra Low-voltage Nanoelectronics Project for a Low Carbon Emission Society	FY2009 – 14
	Development of Infrastructure for Normally-off Computing Technology	11 – 15
	Development of Materials and Process Technology for Advanced Printed Electronics	10 – 18
	Development of Innovative, Low-power Consumption Interactive Sheet Display Technology	13 – 17
	Integrated Photonics-Electronics Convergence System Technology Project	13 – 17
	Development of Next-generation Semiconductor Micro-fabrication and Evaluation Infrastructure Technologies	10 – 15
Health, Medicine	Development of Cell Production and Processing System toward Commercialization of Regenerative Medicine	14 – 18
	Fundamental Technology Development for measuring microRNA in Body Fluids	14 – 18
	Comprehensive Research and Development of an Early stage Diagnosis Method and Instruments for Treating Cancer	10 – 14
Materials	Development of Innovative Structure Materials	14 – 22
	Project for Practical Application of Carbon Nanomaterials for a Low Carbon Emission Society	10 – 16
	Development of Fundamental Evaluation Technology for Next-generation Chemical Materials	10 – 17
	Rare Metal Substitute Energy-efficient Materials Development Project	08 – 15
	Development of Magnetic Materials for High-efficiency Motors for Next-generation Vehicles	14 – 21
	Laser Material Processing Technology Development Project for Next-generation Materials, Etc.	10 – 14

Figure 9

The JST Strategic Basic Research Programs aim to create new technological seeds that will lead to innovation in science and technology (Figures 10 and 11). Figures 10 and 11 show some of recent Core Research for Evolutional Science and Technology (CREST) projects and Exploratory Research for Advanced Technology (ERATO) projects, respectively.

Figure 10


Recent Strategic Basic Research Projects of JST (ERATO) on Nanotechnology
2009
10
11
12
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16
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20
NAKAJIMA Designer Nanocluster Assembly
Research Director: Atsushi Nakajima (Keio Univ)
YODA Supra-integrated Material
Research Director: Tomokazu Iyoda (Tokyo Inst Tech)
KATORI Innovative Space-Time
Research Director: Hidetoshi Katori (Univ Tokyo)
TAKEUCHI Biohybrid Innovation
Research Director: Shoji Takeuchi (Univ Tokyo)
AKIYOSHI Bio-Nanotransporter
Research Director: Kazunari Akiyoshi (Kyoto Univ)
KANAI Life Science Catalysis
Research Director: Motomu Kanai (Univ Tokyo)
SOMEYA Bio-Harmonized Electronics
Research Director: Takao Someya (Univ Tokyo)
ADACHI Molecular Exciton Engineering
Research Director: Chihaya Adachi (Kyushu Univ)
ISOBE Degenerate π-Integration
Research Director: Hiroyuki Isobe (Tohoku Univ)
ITAMI Molecular Nanocarbon
Research Director: Kenichiro Itami (Nagoya Univ)
MINOSHIMA Intelligent Optical Synthesizer
Research Director: Kaoru Minoshima (Univ Electrocom)
SAITOH Spin Quantum Rectification
Research Director: Eiji Saitoh (Tohoku Univ)

Figure 11

Besides the Strategic Basic Research Programs, JST promotes unique programs aimed at innovation (Figure 12).

Other JST Programs on Nanotechnology

S-Innovation (Strategic Promotion of Innovative Research and Development)
Bio-functional Materials
Organic Electronics
Photonics Polymers
Superconductivity System
Spin Currents

Collaborative Research Based on Industrial Demand
Molecular Imaging : Towards Biophotonics Innovations in Medicine
High Performance Magnets : Towards Innovative Development of Next Generation Magnets
Heterogeneous Structure Control: Towards Innovative Development of Metallic Structural Materials
Terahertz–wave: Towards Innovative Development of Terahertz-wave Technologies and Applications

Advanced Low Carbon Technology Research and Development Program (ALCA)
Solar Cell and Solar Energy Systems
Superconducting Systems
Electric Storage Devices
Ultra Heat-Resistant Materials and High Quality Recycled Steel
Biotechnology
Innovative Energy-Saving and Energy-Producing Chemical Processes
Innovative Energy-Saving and Energy-Producing Systems and Devices

Advanced Catalytic Transformation for Carbon utilization (ACT-C)
Creation of Advanced Catalytic Transformation for the Sustainable Manufacturing at Low Energy, Low Environmental Load

Accelerated Innovation Research Initiative Turning Top Science and Ideas into High-Impact Values (ACCEL)	Research Director
Three-Dimensional Integrated Circuits Technology Based on Vertical BC-MOSFETs and Its Advanced Application Exploration	T. Endo (Tohoku Univ)
Development of flexible nitride semiconductor devices with PSD	H. Fujioka (Univ Tokyo)
Fundamentals and Applications of Diamond Electrodes	Y. Einaga (Keio Univ)
Materials Science and Application of Electrides	H. Hosono (Tokyo Inst Tech)
Development of Key Chemical Processes of Extremely High Efficiency with Super-Performance Heterogeneous Catalysts	Y. Uozumi (IMS)
Photonic Crystal Surface-Emitting Semiconductor Laser - Towards Realization of High Power and High Brightness Operation	S. Noda (Kyoto Univ)
Innovative Molecular Structure Analysis based on Self-Assembly Technology	M. Fujita (Univ Tokyo)
The Nanospace Science of PCP for Molecular Control	S. Kitagawa (Kyoto Univ)

Figure 12

By observing the above programs and projects promoted by Japan we can grasp the keywords of R&D areas for priority investment: They are batteries, power electronics, catalysts (catalysts for chemical synthesis, catalysts for artificial photosynthesis, photocatalysts, fuel cell catalysts, etc.), structural materials, sensor devices (for health care, the environment, infrastructure, etc.), and the substitution for critical metals and elements. Some of these areas are briefly reviewed below.

Batteries

Besides the competition in developing high-performance lithium-ion batteries, researches aiming at innovative next-generation batteries are promoted. The goal is to build a system of fundamental technology that enables us to design and manufacture novel batteries with extremely high energy density that the existing batteries can never attain.

Under NEDO's R&D Initiative for Scientific Innovation of New Generation Batteries (NEDO-RISING), a central research hub was set up at Kyoto University, and a project for developing innovative batteries, which encompasses basic research and practical application, is underway based on industry-government-academia collaboration. Large-scale cutting-edge research facilities such as SPring-8 and J-PARC are jointly used by the participants. The initiative promotes basic research and innovation for next-generation batteries based on collaboration among Japanese organizations. Also, under JST's ALCA-SPRING project, a joint research center was set up at the National Institute for Materials Science (NIMS), and a large-scale organized R&D project started in 2013 FY, in which participating researchers from universities and national institutions are categorized into four groups, each of which has a primary objective. The scale of these efforts surpasses that of similar efforts in other countries, since most of the relevant Japanese researchers of academia are involved in these R&D projects.

Power Electronics

The power semiconductor devices that are currently widely used are based on silicon (Si), and their performance is improved through advances in microfabrication technology, improvement in wafer quality, introduction of new manufacturing processes such as low-temperature manufacturing, and improvement in device structure (super-junction MOSFETs and generational improvement in insulated-gate bipolar transistors, etc.). However, due to the material properties of silicon, many have pointed out limits to device performance. It is thus hoped that power semiconductor devices based on a semiconductor with a band gap wider than that of silicon will soon be ready for practical application. Candidate semiconductors include silicon carbide (SiC) and gallium nitride (GaN), for which both high breakdown voltage and low on-resistance are in principle achievable. In the process of realizing practical application of such power semiconductor devices, R&D-related challenges that need to be addressed include improving crystal quality, increasing wafer size, controlling material properties, and improving device structure, manufacturing processes, high-precision thermal design and power management, module and circuit technology, and peripheral and passive components.

TIA-nano is an R&D center for power semiconductor devices based on wide band gap semiconductors, and development efforts are made by the Tsukuba Power-Electronics Constellations (TPEC), which is a collaborative research entity for open innovation and takes advantage of private-sector resources. Furthermore, TPEC utilizes the SiC-related fundamental technologies and prototype lineup accumulated by AIST. Under JST's Super Cluster Program, R&D for SiC and GaN devices is conducted based on interregional cooperation between the Kyoto region and the Aichi region which constitute the core cluster.

A large-scale project related to power semiconductor devices under the Cabinet Office's FIRST Program entitled "Innovative SiC Power Electronics Technology toward Low-Carbon Society" ended at the end of FY2013. In 2014, a project called "Next-Generation Power Electronics" started under the Strategic Innovation Promotion Program (SIP). The project is based on industry-academic collaboration for developing a wide range of technologies for SiC, GaN, gallium oxide (Ga_2O_3), and diamond, including technologies related to substrate crystal growth, epitaxial growth, devices, circuit modules, packages, and thermal design. The program is administered in tandem with METI's Project for Developing Technologies for Next-Generation Power Electronics (2009-2019) which is mainly aimed at developing wafers, power devices, and modules that are based on SiC.

Structural Materials

Projects related to metallic materials include the following: Collaborative Research Based on Industrial Demand project in the JST INDUSTRY–ACADEMIA COLLABORATIVE R&D PROGRAMS entitled "Heterogeneous Structure Control: Towards Innovative Development of Metallic Structural Materials" (since 2010), which is intended to lay a path for developing next-generation metallic structural materials; the JST Advanced Low-Carbon Technology R&D Program project entitled "Ultra Heat-Resistant Materials and High Quality Recycled Steel" (since 2011), which mainly promotes development of technologies for heat-resistant materials and coatings to be used in steam/gas turbines for power generation and transportation machines; and MEXT's Elements Strategy Project (for establishing research centers) (since 2011), which is aimed at laboratory-based development of structural materials that do not use rare elements.

In 2014, the Research Center for Structural Materials was set up at NIMS, and the Tsukuba Open Plaza for Advanced Structural Materials (TOPAS) started its activities as a part of the research center to become a platform for industry-academia-government collaboration.

Programs related to carbon-fiber-reinforced polymers (CFRPs) include those by METI: the program entitled "Development of Fundamental Technologies for Innovative Carbon Fibers" (since 2011), which is intended to establish fundamental technologies that are necessary for new carbon fiber manufacturing processes; and the program entitled "Development of Technologies for Manufacturing and Processing of Next-Generation Structural Components (Composite Structure)" (since 2013), which promotes implementation of the technology for monitoring the health of aircraft-grade CFRP structures and development of technologies for manufacturing process monitoring. Also, under MEXT's Center of Innovation Science and Technology based Radical Innovation and Entrepreneurship Program ("COI STREAM"), a program entitled Construction of Next-Generation Infrastructure Systems Based on Innovative Materials started, with the Kanazawa Institute of Technology designated as the central institution.

As a program dealing with structural materials in general, METI's Research Program for Pioneering the Future entitled "Development of Technologies for New Innovative Structural Materials" (since 2013) aims at drastic reduction of the weight of automobiles and other transportation machines and promotes the development of steels, nonferrous metals (aluminum, titanium, magnesium), and CFRPs, as well as bonding techniques for these materials. To promote the program the Innovative Structural Materials Association (ISMA) was established, and 19 companies and an independent administrative institution participate in the development of materials (steel, aluminum, titanium, and magnesium), production processes, and bonding techniques. As for CFRPs, Nagoya University and 17 companies participate in the development of carbon-fiber-reinforced thermoplastics (CFRTP) to reduce the weight of mass-produced cars.

The project entitled "Innovative Structural Materials," which started in 2014 under SIP of the Cabinet Office, lists as R&D items heat-resistant alloys and intermetallic compounds, as well as ceramic coatings, aircraft-grade resins, and fiber-reinforced plastics (FRPs). Among the 26 selected projects for the program, eight projects (involving two research centers) belong to the area of heat-resistant alloys and intermetallic compounds and plan to develop processing technologies for nickel-based alloys, titanium alloys, and titanium-aluminum as materials used for aircraft engines. Also, six projects (involving one research center) belong to the area of aircraft-grade resins and FRP and plan to develop CFRTP for aircraft engine fan cases/blades, technologies for autoclave-free molding of structural materials used for aircraft fuselages, and technologies for molding large components.

The Elements Strategy

The cooperative measures that started in 2007 between the Elements Strategy Project (by MEXT) and the Rare Metal Substitute Materials Development Project (by METI) continue to this day. In 2012, MEXT started the Elements Strategy Project (for Creating Research Centers) as a ten-year project. For this project and the related project by METI (the Research Program for Pioneering the Future), there is a governing board involving both ministries.

2.3 Research Community and Researchers

One of the most serious problems in Japan is a lack of long-term policies that tackle various issues in education and human resource development, which significantly hinder progress in the field of nanotechnology and materials. These issues include, for example, a reduction of young people's interest to science, a rapid decline in the number of students wanting to study engineering and young researchers' preference for domestic opportunities. Most programs for human resource development are stopgap or short-term programs and are not based on a strategic plan. This problem is most serious in the long run for the field of nanotechnology and materials which requires human resources with a broad view over different fields.

2.3.1 Trends in Academic Societies

While academic societies in the United States are increasing their membership, the Japan Society of Applied Physics, the Chemical Society of Japan, and the Physical Society of Japan have seen their membership declining. Over a ten-year period, the Chemical Society of Japan lost about 6,000 members, and each of the other societies lost about 2,000 members. In particular, the number of members from industries is decreasing.

With regard to the proportion of foreign members, it is about 1% for academic societies in Japan, whereas it is about 40% for academic societies in the United States. Japan thus cannot bear comparison with the United States in terms of globalization of membership. Today, government investments in the field of nanotechnology and materials are growing faster in Asia than they are in Europe and the United States. Despite this shift toward Asia, Japanese academia, which has led the world in advanced science, lags behind in terms of globalization and cannot attract researchers from other Asian countries, to which Japanese academia are responsible. Well before the economy became globalized, the science world should have become globalized.

As one of a few examples of successful international activities in the past several years, the International Center for Young Scientists (ICYS) of NIMS requires that communication be conducted in English and encourages researchers from other countries to stay in Japan by offering tenure-track opportunities. Also, the World Premier International Research Center Initiative (WPI) has succeeded in increasing the number of foreign researchers at the International Center for Materials Nanoarchitectonics (MANA).

2.3.2 Trends in the Research Community Indicated by Research Papers

In Japan, the number of researchers authoring papers in the field of nanotechnology and materials is about 35,000 as of 2013, which ranks the country third after China and the United States. Over the past ten years, while the number of such researchers increased twofold in Europe and the United States and threefold in China and South Korea, it only grew by 50% in Japan. In passing, one should note that since the number of journals recorded in databases has increased, this rate of increase is not necessarily proportional to the growth rate of the researcher population.

It is said that in Japan corporate researchers stopped writing papers. Statistics show that the number of researchers in major countries has increased over the past 20 years mainly in the United States, Europe, and Japan, and that the rate of increase since the turn of the century for China and South Korea is remarkable. As of 2010, the number of researchers in various countries is as follows: the United States (1,413,000), China (1,211,000), Japan (843,000), Germany (327,000), South Korea (264,000), and the United Kingdom (235,000). The proportion of corporate researchers is high for the following countries: the United States (81.6% in 1999), South Korea (76.5% in 2010), and Japan (74.8% in 2011, full-time equivalents). The proportion is relatively low in major European countries: the United Kingdom (34.2% in 2010), France (57.0% in 2009), and Germany (56.8% in 2010). The proportion for China (61.1% in 2010) is close to that for Germany and France.

2.3.4 Trends in Education Policies

Nanotechnology is a field that is expected to create new fields and industrial technologies by promoting integration of different fields and cooperation among organizations. The United States and Taiwan have implemented measures to build a system providing educational continuity (throughout primary and secondary education).

The United States plans to place nanotechnology at the core of continuous education in science and technology, and shared facilities of the National Nanotechnology Infrastructure Network (NNIN) are used to prepare curriculums and textbooks and hold training programs for teachers. Taiwan has promoted such continuous education at a faster pace than the United States and has already prepared relevant textbooks (in both Chinese and English). In South Korea, textbooks written in English (edited by the Korea

Nanotechnology Researchers Society), such as The Introduction to Physics of Nanoscience, Nanochemistry, and Nanoelectric Devices, are available to graduate students and young researchers.

In Japan, programs for human resource development are generally temporary, and systematic long-term educational programs are almost nonexistent. The Osaka University Institute for Nanoscience Design was established in 2004 under the Human Resource Development Program for Emerging Fields, which is funded by MEXT through its Special Coordination Funds for the Promotion of Science and Technology. Over a period of five years, 1,100 graduate students studied at the institute and 700 completed their studies. The institute also provides educational training to many professionals. The institute was funded for four years by another program (Special Funds for Education and Research) to maintain its operational continuity and has improved its nanotechnology education and training programs in which the topics covered include social acceptance of nanotechnology. A significant portion of the institute's activities is self-funded, and there is no guarantee for its continued operation. Therefore, policies providing incentives for self-funding, such as matching funds, will be needed.

2.4 Global Trends in R&D

2.4.1 Trends in R&D in Japan

The following discusses trends in R&D in Japan in five areas and presents comparisons with global trends.

Nanotechnology and Materials Related to the Environment and Energy

There is great global interest in solar cells, artificial photosynthesis, fuel cells, thermoelectric conversion, battery devices, power semiconductor devices, and catalysts for green processes. This is because they are closely related to use of renewable energy, efficient storage and conversion of energy, and reduction in CO_2 emissions. In many of the aforementioned areas, research activities are increasing. In particular, research on battery devices is globally intensifying.

From basic research to commercialization, Japan leads the rest of the world, especially in solar cells, fuel cells, and batteries. However, in the commercialization of solar cells and catalysts for green processes, activities are stagnant or declining due to competition with China and South Korea.

Nanotechnology and Materials Related to Health and Medical Care

In the area of nanoscale drug delivery systems (nanoscale DDSs), activities are increasing, from basic research to commercialization. Drugs based on nanoscale DDSs are being clinically tested and launched in the market, and there is tremendous activity in this area. Due to advances in nanoscale DDSs with contrast medium, R&D activities in bioimaging are on the rise.

While the level of basic research in this area continues to be high in Japan, this has not resulted in a high level of competitiveness in terms of commercialization, except for bioimaging (in which Japan ranks among the world's leading countries).

Nanotechnology and Materials Related to Social Infrastructure

Worldwide, R&D efforts are active in the areas of structural materials, separation membrane materials, and sensor devices.

Japan shows its strength in metallic structural materials, from basic research to commercialization. However, compared to Europe and the United States, Japan is weak in applied research on composite materials (e.g., CFRPs), basic research on membranes for water treatment, and applied research and commercialization in the area of sensor devices.

Nanotechnology and Materials Related to Information, Communications, and Electronics

There is little change in the level of R&D activities for technologies that have long been subject to R&D efforts (e.g., ultra-low power consumption nanoelectronics and microelectromechanical systems (MEMS)), but increased activities are observed for new technologies (e.g., two-dimensional atomic layers).

Japan has traditionally shown its strength in the areas of spintronics and organic electronics, but lags behind Europe and the United States in the area of two-dimensional functional atomic layers. Compared to the past, Japan's weakness in the commercialization phase is worrisome.

Fundamental Science and Technology for Nanotechnology and Materials

The foundation of the field of nanotechnology and materials consists of a wide range of areas of materials research such as design and control technologies, synthesis and processing, measurement and analysis, and calculation. In particular, areas in which R&D is active worldwide include nanospace materials, biomimetics, and data-driven materials design.

Basic research in Japan has been conducted at high levels, and Japan particularly shows its strength in its Elements Strategy and in nanoscale measurement (with electron microscopes, synchrotron radiation, and X-rays). Japan lags behind Europe and the United States in terms of applied research and commercialization in areas that are attracting attention, such as space-controlled materials, biomimetics, and data-driven materials design (materials informatics).

2.4.2 Global R&D Trends

The following discusses recent global R&D trends in Figure 13.

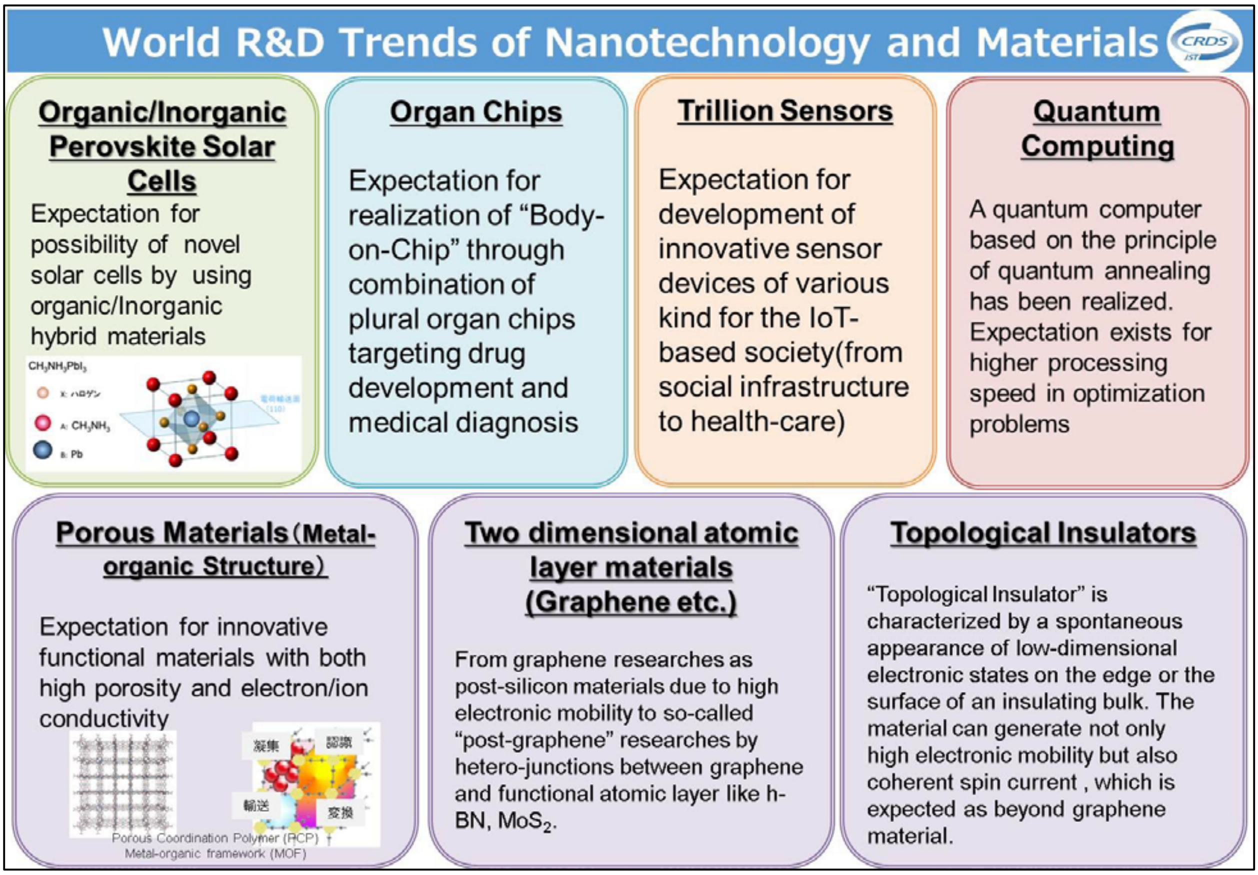

Figure 13

Hybrid Perovskite Solar Cells

Currently, the solar cells based on lead halide perovskite, which is an organic-inorganic composite material developed by Tsutomu Miyasaka (Toin University of Yokohama), already achieves a conversion efficiency of about 19%. As conversion efficiency rapidly increases, intense international competition in R&D has begun among Japan, the United States, Europe, China, South Korea, and other countries.

Organ Chips

Research on reproduction of part of a biological reaction or cellular response has been sporadically conducted. Since the Ingber group at Harvard University reported a three-dimensional culture model called the "lung-on-a-chip", rapid progress has been made in research on integrating tissues and organs on microdevices. In the United States, in 2012 the Defense Advanced Research Projects Agency (DARPA) and the National Institutes of Health (NIH) independently started a five-year, 70-million-dollar project. The goal is to increase efficiency in drug discovery by developing for new three-dimensional culture models (organ chips) that mimic functions of biological tissues and organs. It is expected that a “body-on-a-chip” enabling analysis of a whole-body response to an intended action will be realized by combining multiple organ chips, and that it will be applied not only to drug discovery but also to a wide range of areas including pathological analysis.

Trillion Sensors

In 2013, the Trillion Sensors project started in the United States. The project aims at use of one trillion sensors per year in ten years (by 2023). The use of one trillion sensors per year means that each of the world's 7 billion people will use 142 sensors per year, the scale being 100 times the present demand. Sensors will be used in all aspects of medical treatment, health care, agriculture, social infrastructure, and other sectors and activities. Big data will be used in a wide range of situations and will significantly change society and people's lives. Concepts like the IoT and machine to machine (M2M) describe a similar world. While communications and networks play the central role in these concepts, the Trillion Sensors project centers on sensor devices.

Quantum Computers

In 2013, the Canadian company D-Wave sold its second-generation quantum computers, which were based on quantum annealing and were equipped with a superconducting, 512-qubit processor, to Google, NASA, and the Universities Space Research Association (USRA). These organizations created the Quantum Artificial Intelligence Laboratory with these quantum computers at its core. The lab has started research mainly on machine learning, which has stimulated R&D on quantum computers. Activities of the lab have attracted attention from industry. The quantum annealing process was devised in 1998 by Tadashi Kadowaki and Hidetoshi Nishimori of the Tokyo Institute of Technology. Its advantages are that it is applicable to optimization problems, does not require a program, is robust against noise, and is faster than the classical simulated annealing process. Its disadvantages are that it does not perform general-purpose quantum computation, and that researchers have not found useful problems for which a dramatic increase in computational speed is guaranteed.

Advances have been made in technologies related to quantum information, which forms the foundation of general-purpose quantum computers. A quantum operation involving multiple qubits requires an error-tolerant arithmetic circuit. Since 2014, there have been reports on control of quantum gates and reading of qubits that are performed above the 99% accuracy level that is considered necessary to create code for surface code quantum computation with error tolerance. Such success is attributed to an increase in superconducting qubit coherence time (over 100 μs), which has dramatically improved accuracy in controlling and observing qubits.

Two-Dimensional Functional Atomic Layers (Graphene, etc.)

The 2010 Nobel Prize in Physics spurred active research on graphene all over the world.

Yet the current trend in the world is a major shift from research on graphene itself as an atomic layer to so-called post-graphene research, which studies heterojunctions between graphene and a functional atomic layer such as hexagonal boron nitride (h-BN) and MoS_2. Notable technological trends include the development of successive heteroepitaxial growth technology of two-dimensional functional atomic layers of graphene, h-BN, and dichalgenide semiconductors whose thickness is controlled on the order of atomic layers, and its linkage with analytical technologies for material structures and material properties.

With regard to industrial application of graphene materials, it is expected that application in green energy products, such as transparent electrodes for touch panels and solar cells, that are based on technologies to mass-produce large graphene films and application in batteries will be realized first, followed by application in flexible thin-film transistors based on two-dimensional dichalcogenide semiconductors such as MoS_2 and WS_2. As for applied research on functional devices, focus is shifting from application of the material properties of graphene itself to application of material properties and functions resulting from the heterojunction of two-dimensional functional atomic layers. Examples of the latter include resonant tunneling and spin injection based on the heterojunction resulting from h-BN sandwiched between two layers of graphene.

Topological Insulators

As research accelerates on graphenes with exotic two-dimensional electronic states and atomic layers of transition metal chalcogenide compounds, attention is being paid to topological insulators in which a two-dimensional electronic state spontaneously emerges on the surface of a three-dimensional material (with the electronic state being different from that in the interior of the material). Topological materials whose interior becomes an insulator exhibit not only high mobility resulting from the surface electronic state with zero mass (which is similar to that of graphene) but also coherent spin current. There are high hopes for application of these phenomena. As a related matter, a finding by a group of American and European researchers in 2014 that the topological insulator has the greatest ability of current-induced magnetization reversal by spin-transfer torque has attracted much attention. Many such “beyond graphene” electronic functions are predicted by theory, and experimental verifications are constantly performed. In the case of a strongly magnetic topological insulator, Hall resistance arising without an external magnetic field is further quantized. Chinese researchers and subsequently Japanese researchers reported their successful verification experiments for this abnormal quantum Hall effect.

Metal-Organic Frameworks

In the past, porous compounds were mainly crystalline materials containing metal ions (zeolites, etc.) or amorphous materials consisting only of organic substances (carbon-based materials). Omar Yaghi (University of California, Berkeley) and Susumu Kitagawa (Kyoto University) and colleagues established the concept of a metal-organic framework (MOF). It is a new kind of porous material with an infinite skeletal structure created by linking organic ligands through coordinate bonding with metal ions (i.e., obtained from simple compounds through a simple reaction). The concept provided important guidance for subsequent designs of porous structures. Reports on MOFs suddenly increased around 2008, and researchers from various fields, such as coordination chemists and polymer chemists, participate in R&D efforts.

The structures of MOFs have a high level of porosity. Some researchers successfully created materials with both high porosity and electronic/ionic conductivity. Also, in some examples, transport of gas molecules in the solids allows for new ways to separate gases.

Due to the electronic conductivity of MOFs, they are used in capacitors. MOFs that are stable at high temperatures are used as catalysts for activation of small-molecule gases. Therefore, MOFs are also important as functional materials.

2.4.3 Main Achievements in Japan (Past Ten Years)

For more than half a century as an advanced country, Japan has continuously been a leader in academic research, technological development, and industrial activity that have produced actual products in the field of nanotechnology and materials and Japan has accumulated scientific knowledge and technologies. Since the turn of the century, R&D activities in Japan have constantly produced technological results that have attracted the world's attention, and efforts have been made to put those results into practical use. Japan is clearly one of the leading countries in R&D in nanotechnology and materials.

Figure 14 shows examples of results of R&D in science and technology that have been produced by universities and public research institutes, attracting the world's attention. These results are expected to be put into practical use in the future.

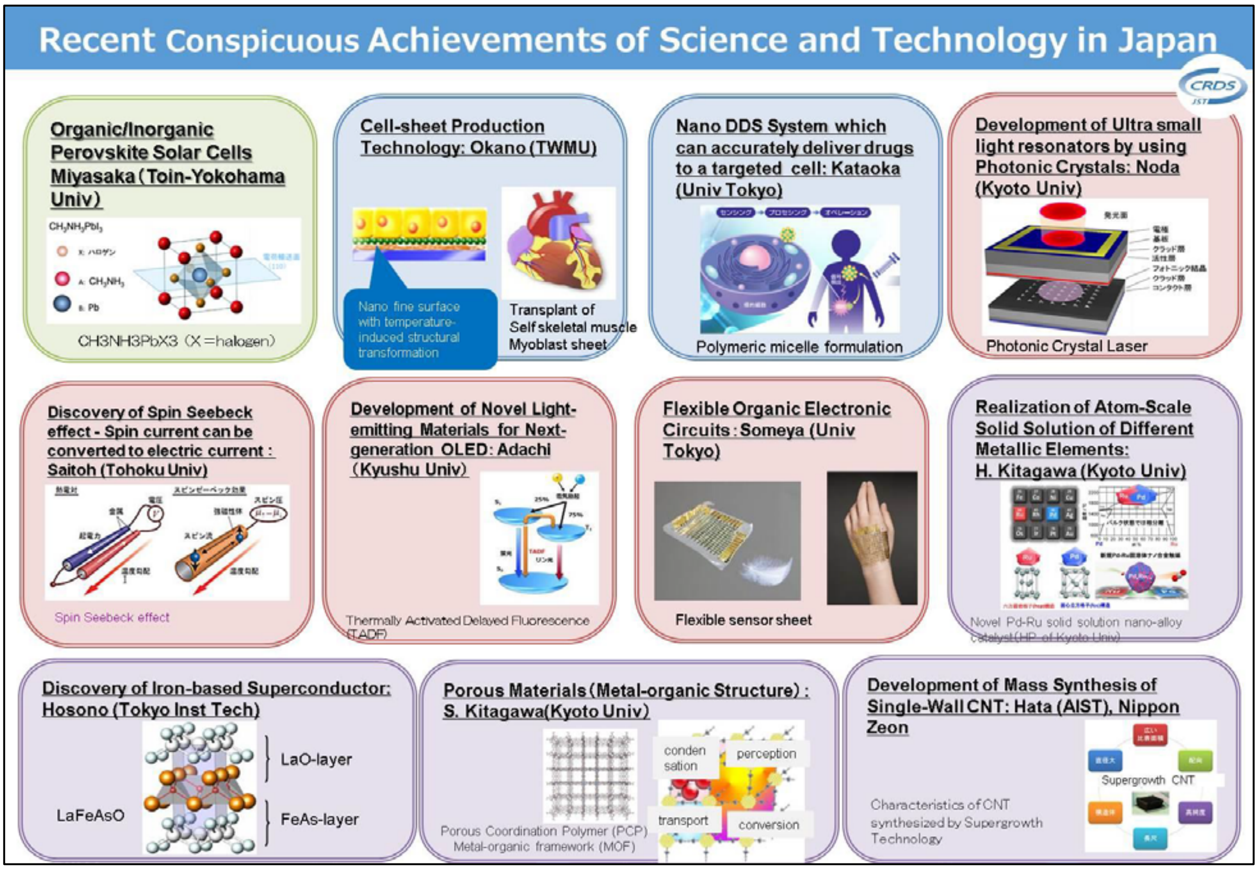

Figure 14

2.4.4 International Comparison of Output (Research Papers) in Science and Technology (Output of R&D)

This section summarizes the results of research in nanotechnology and materials, using information on research papers that the CRDS analyzed based on Elsevier's Scopus database.

As a general trend in research papers, the position of China has improved in the last ten years. The country ranks first in the world in terms of quantity (number of papers). Also, in terms of quality, China became number one as of 2011. (Here, the top 10%most cited papers are considered as quality papers.) As for Japan, little improvement is observed in terms of both quality and quantity.

(1) In terms of number of papers produced (Figure 15), China has been first since 2011, followed by the EU, the United States, and Japan. (Fractional counting is used here: If a researcher from country A coauthors a paper with a researcher from country B, each country receives a count of 0.5.) The rate of increase for China is outstanding, and the number for China is approximately twice that for the United States. The number for Japan tended to increase slightly until 2009, but has declined or changed little since then.

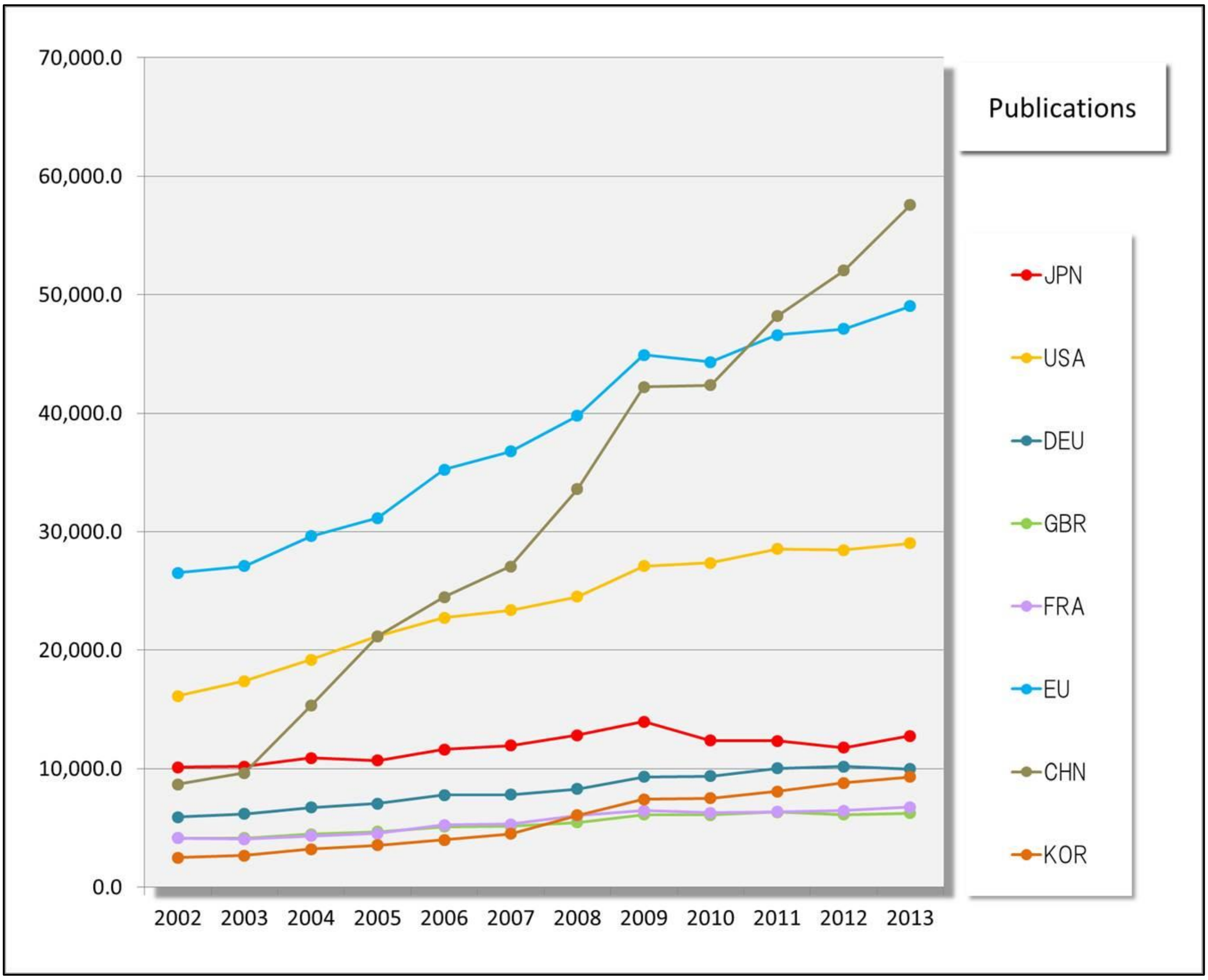

Figure 15

(2) In terms of the number of papers among the top 10% most cited (Figure 16), countries are ranked in the following order: the EU, China, and the United States. Here, too, a rapid increase for China is observed. Japan was in the second place in 2002, following the United States, but presently falls behind China, the United States, and Germany. The number for Japan is almost the same as that for South Korea.

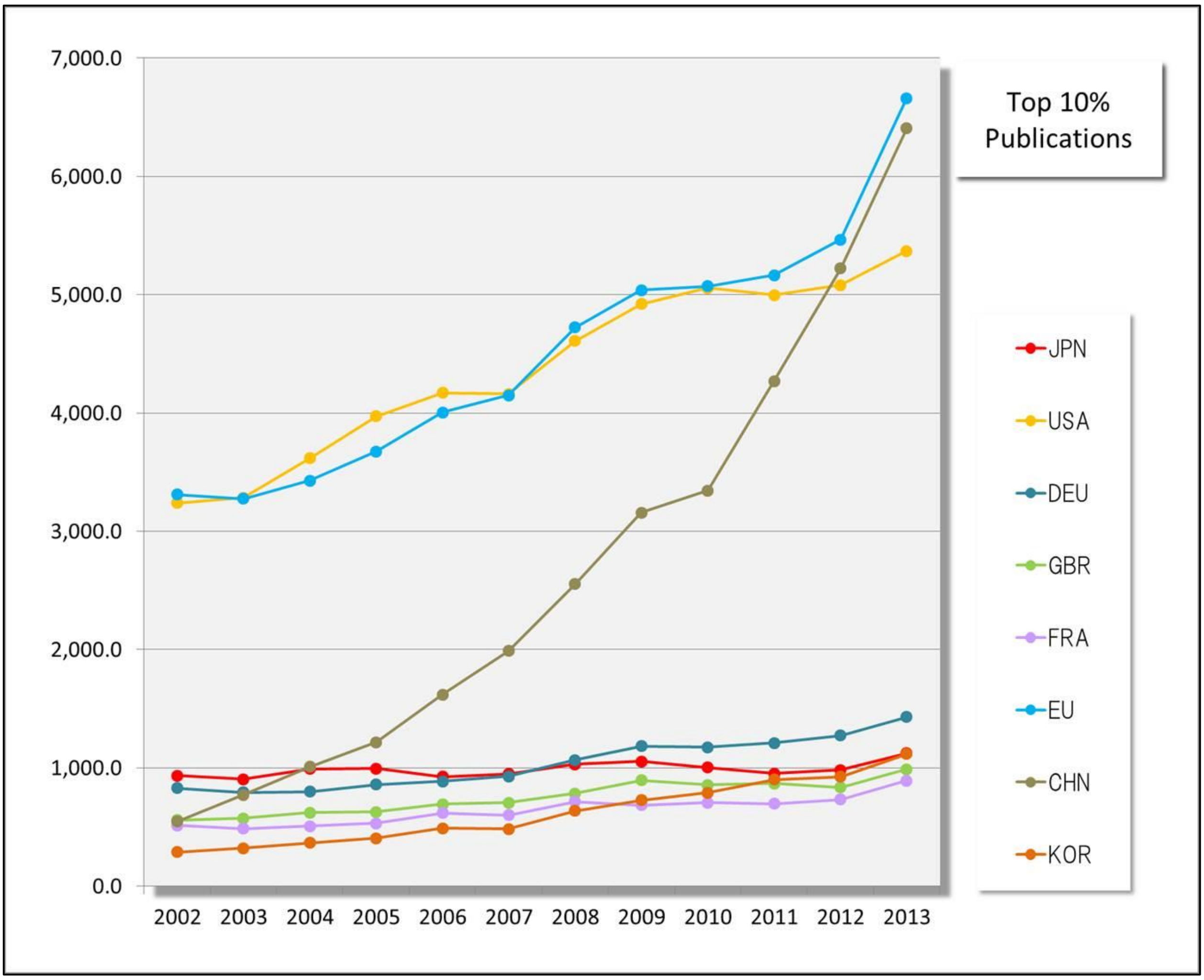

Figure 16

(3) Comparison of countries for each subfield of the nanotechnology and materials field (the environment and energy; health and medical care; social infrastructure; information, communications, and electronics; fundamental science and technology) reveals characteristics of each subfield (Figures 17-21).

Among these subfields, research activities related to the environment and energy have the greatest momentum, and one can see that China and South Korea have made substantial efforts here. Moreover, it is notable that in terms of the number of papers among the 10% most cited, the position of China rapidly improved and surpassed Europe and the United States in 2013.

In terms of number of papers, Japan ranks around third or fourth (disregarding the EU) behind the United States and China in every subfield. In terms of the number of papers among the 10% most cited, the position of Japan is similar to that of Germany or South Korea or is often fifth, behind these countries. For Japan, as far as the number of papers among the 10% most cited is concerned, the number is highest in fundamental science and technology, and the country's position is lowest among the major countries in health and medical care.

- Nanotechnology and materials related to the environment and energy (left: number of papers; right: number of papers among 10% most cited)

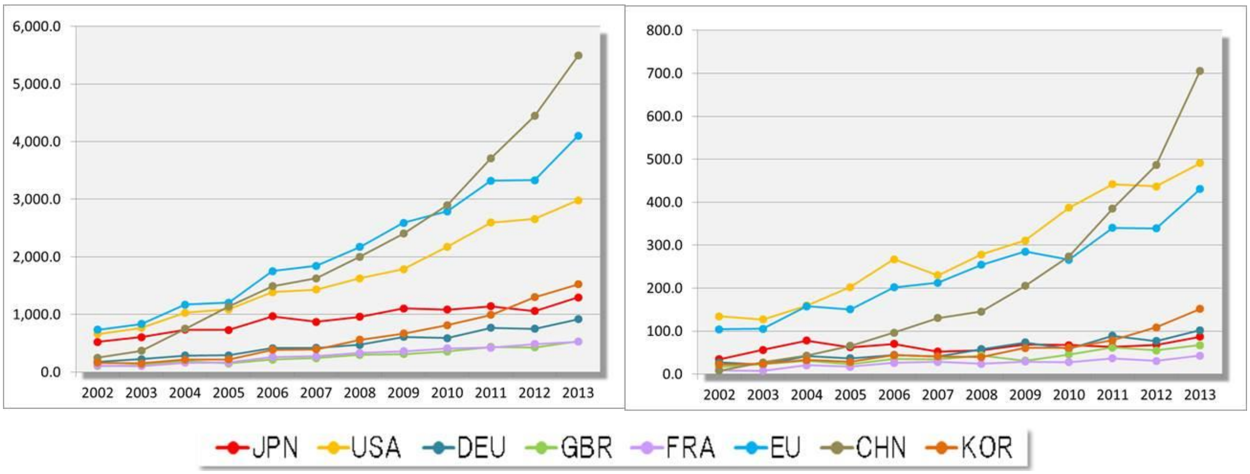

Figure 17 Nanotechnology and materials related to the environment and energy

- Nanotechnology and materials related to health and medical care (left: number of papers; right: number of papers among 10% most cited)

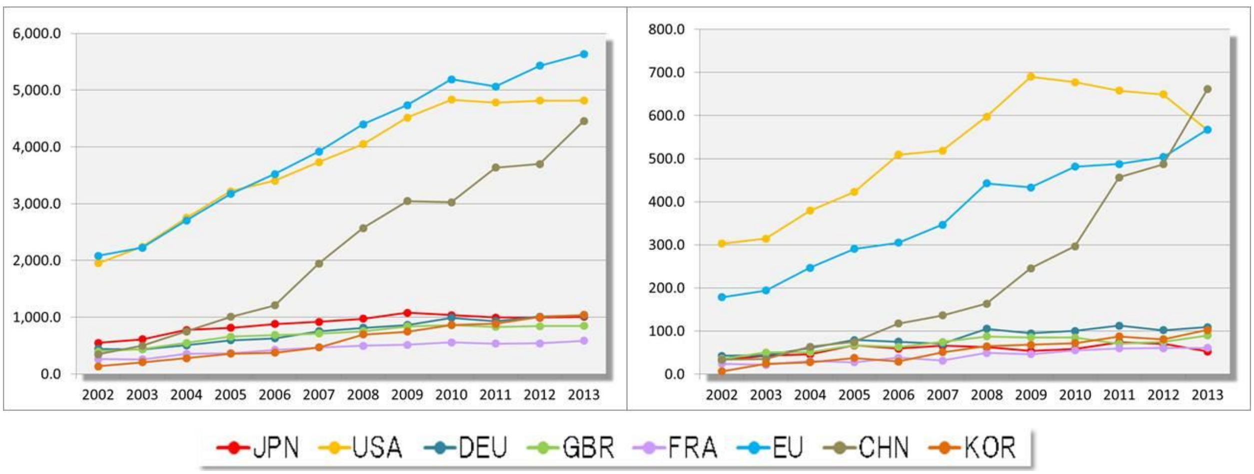

Figure 18 Nanotechnology and materials related to health and medical care

• Nanotechnology and materials related to social infrastructure (left: number of papers; right: number of papers among 10% most cited)

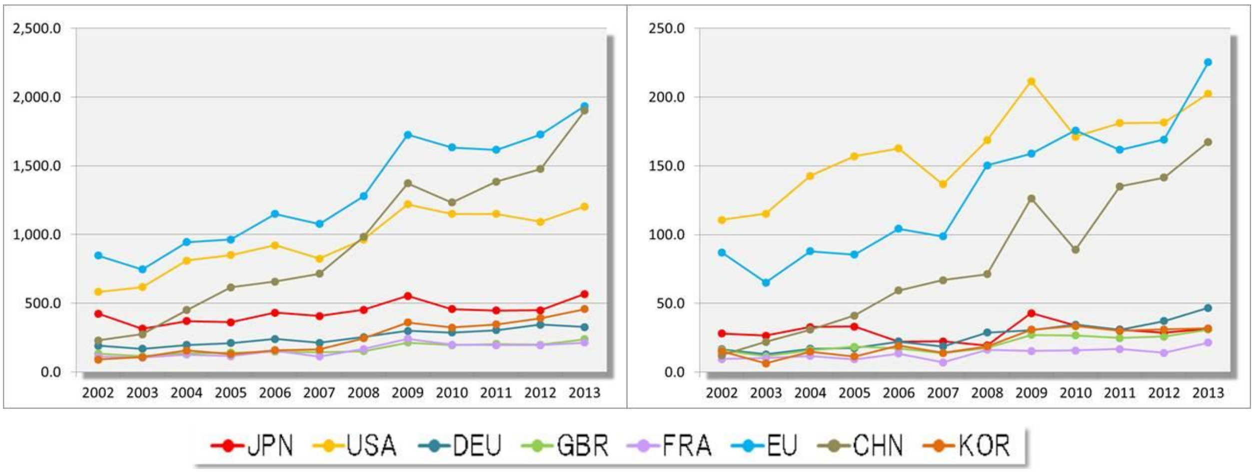

Figure 19 Nanotechnology and materials related to social infrastructure

• Nanotechnology and materials related to information, communications, and electronics (left: number of papers; right: number of papers among 10% most cited)

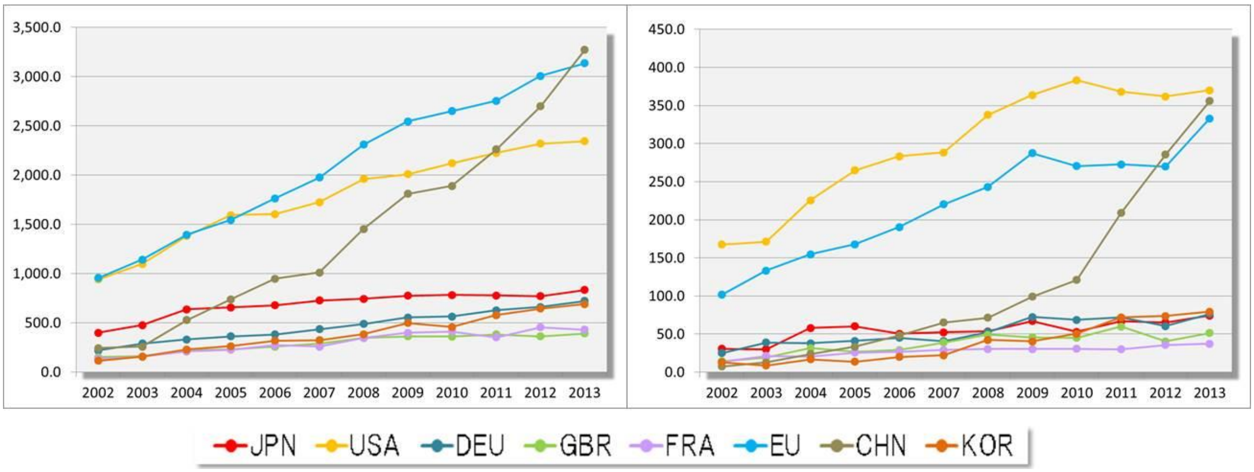

Figure 20 Nanotechnology and materials related to information, communications, and electronics

- Nanotechnology and materials related to fundamental science and technology (left: number of papers; right: number of papers among 10% most cited)

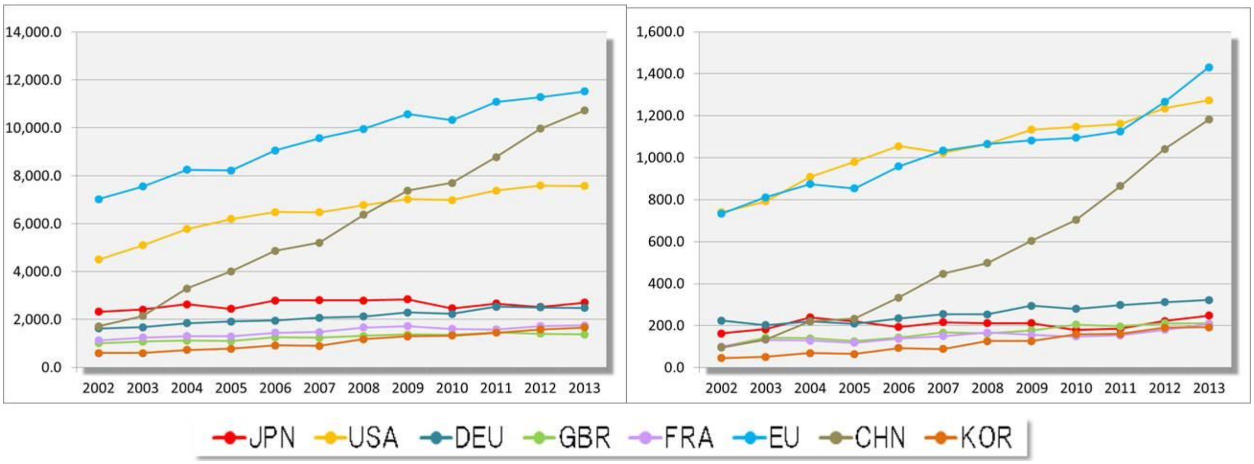

Figure 21 Nanotechnology and materials related to fundamental science and technology

2.5 Trends in Industry

Japan's components industry produces functional materials and many other products that capture a large global market share even though the size of each market is small. Japan thus has significant market presence for the components industry as a whole. According to data on the global market share for each product, the share of Japanese companies is large for automobiles, precision devices such as digital cameras, and relevant components. However, for products like cellular phones and semiconductor devices, global market share of Japanese companies is tending downward, although there are still many Japanese companies that produce relevant components and have a large global market share.

There are many products for which Japanese companies have gained a large global market share. Examples include semiconductor materials, materials for LCDs, materials for lithium-ion batteries, carbon fiber, and separation membranes for water treatment. At the same time, it should be noted that there are materials for which Japanese companies are significantly losing their market share due to rapidly growing competition with China and South Korea. They include some materials for LCDs, such as LCD photoresists and color filters, and materials for lithium-ion batteries.

Generally speaking, in contrast to materials, nanotechnologies are used in quite diverse ways. For example, they are used in various processes and in component materials of devices. It is thus difficult to judge from final products how nanotechnologies are utilized, which makes their usefulness less obvious. It has been found that nanotechnology-related products tend to be rapidly adopted soon after they are launched in the market. According to the market prediction made by the British company BCC Research, the size of the global market for nanotechnology-related products was 26 billion dollars for 2014. This market is expected to grow to 64 billion dollars by 2019 with an average annual growth rate of 19.8%.

Over a period of 12 years from 2000 to 2012, the share of Japanese exports in worldwide exports increased as follows: 7.4% to 10.0% for chemical products; 9.8% to 13.2% for raw material products (steel, nonferrous metals, etc.); and 21.0% to 23.5% for transportation equipment. Meanwhile, the share decreased as follows: 26.5% to 17.9% for electric equipment; and 21.5% to 20.1% for general machineries. For 2012, the top three product categories for which Japan has a large export share are transportation equipment (23.5%), general machineries (20.1%), and electric equipment (17.9%).

It should be noted, however, that the proportion of overseas production for the Japanese manufacturing industry has increased to about 20% from 11.4% in 2000, and that this fact has led to an increase in both exports of components and materials and imports of final products.

Automobiles

The automobile industry is quite large in terms of its market size and range of components used, and automobile innovations are closely linked with materials technologies.

Steel, aluminum, and plastics are the three major materials required for automobile production, and other important materials include rubber used for tires, glass for the windshield, ceramics for sensors, and catalysts for cleaning exhaust gas.

Semiconductor Devices and Electronics

The size of the global market for the entire electronics industry, which produces personal computers, tablets, smartphones, television sets and other digital home appliances, and semiconductor devices, is about 250 trillion yen and surpasses the size of the global market for the automobile industry. The electronics industry, in which Japan was a major player, has been globalized. The model of product development has significantly changed due to digitization, which is typically seen in semiconductor technologies, and the emergence of other Asian countries. In particular, it is a well-known fact that the market share of Japanese companies for products like personal computers, cellular phones, and television sets has significantly declined. At the same time, Japanese manufacturers still have a large global market share for semiconductor materials and electronic components. However, South Korean, Chinese, and Taiwanese companies have dramatically expanded their production in some electronic components and materials, such as memory chips whose sales have steadily increased due to the growing markets for tablets, smartphones, and the like.

Rechargeable Batteries

As countries try to create a low-carbon society, the importance of batteries is rapidly increasing. Based on their properties, batteries can be roughly categorized as follows: those suited for dealing with medium- and long-cycle output fluctuation, such as sodium-sulfur (NAS) batteries; those suited for dealing with short-cycle output variation, such as lithium-ion batteries and nickel-metal hydride batteries; and those suited for any type of use, such as redox flow batteries.

For automobiles, batteries that are lightweight, compact, and high capacity are demanded because the world is moving into the era of electric and hybrid vehicles. Batteries installed at a fixed location enable users to store electricity at night and use the stored electricity during the day when demand for electricity rises. For personal computers and mobile devices like smartphones, the importance of compact high-capacity batteries never changes. Lithium-ion batteries satisfy demand for such batteries. Their main component materials are cathode active materials, anode active materials, electrolytes, and separators, and Japan has had a large global market share for these materials. The size of the global market for batteries is expected to reach 20 trillion yen by 2020.

Lithium-ion batteries are predicted to be a large part of the market for rechargeable batteries. In 2000, Japanese companies dominated the global market with a global market share of 93%, but in 2014, their global market share was down to 22% due to factors like the emergence of South Korean and Chinese manufacturers. Although the market share of Japanese companies for materials used in batteries, such as anode materials, cathode materials, and separators, is still high, there are concerns that as their market share for rechargeable batteries falls, their market share for related components will also decline.

Solar Cells and Fuel Cells

With regard to solar cells, due to price competition that is occurring globally, a considerable number of manufacturers in Japan of raw materials and wafers, as well as of solar cells and related equipment have had to exit the market or had stagnant business. At the same time, because of feed-in tariff (FIT) systems, the number of mega-solar power plants located in various parts of Japan and the quantity of solar modules for houses rapidly increased. Concentrator photovoltaic systems can drastically reduce the amount of solar cells needed and thus have started to attract attention as a new technology for low-cost power generation. An increasing number of companies are entering the market. It is expected that demand will increase in regions that receive a large amount of direct solar radiation.

Fuel cells for household use were introduced to the market in 2009. The size of the global market for fuel cell systems was approximately 70 billion yen in 2011 and is expected to exceed 5 trillion yen in 2025 as fuel cell automobiles are introduced to the market in 2015 and the market for them is expected to expand.

Carbon Fibers and Composite Materials

Carbon fibers are lightweight and strong and thus meet the needs of the era of energy saving. The market for carbon fibers is expected to expand in the areas of transportation equipment (aircraft, automobiles, etc.) and energy (wind power generation, etc.) The market size is currently about 200 billion yen and is expected to increase at an annual rate of approximately 20% and reach 450 billion yen in 2020. If molded products made of CFRPs are included, the market size is expected to reach 2.5 trillion yen. As of 2012, the global market share of three Japanese companies was about 70%, and they are expected to maintain a large market share.

Separation Membranes for Water Treatment

Separation membranes for water treatment can be roughly categorized into the following: reverse osmosis (RO) membranes, nanofilter (NF) membranes, ultrafiltration (UF) membranes, microfiltration (MF) membranes, and ion-exchange membranes. They are widely used to desalinate water, produce ultrapure water, condensation treatment at electric power plants and chemical plants, and recycle wastewater. The use of separation membranes is expected to expand as an increasing number of overseas regions with limited water resources consider desalination of seawater. The size of the entire market in 2012 is close to 200 billion yen, and the global market share of Japanese companies is about 50% for RO and NF membranes and approximately 40% for UF and MF membranes.

2.6 Policies for R&D and Innovation around the World: Building a Supportive Environment

Advanced technologies have become increasingly sophisticated, integrative, and interdisciplinary. Since observation, assessment, and control of phenomena at the atomic and molecular level are especially necessary in the field of nanotechnology, it is difficult for companies and individual research institutes to maintain not only a research group whose expertise covers a sufficiently wide range of specialized fields, but also expensive equipment for experiments and specialists who can fully utilize such equipment.

At the same time, competition in R&D has intensified at a global scale, and demand has grown for greater development speed. Research centers for open innovation are seen in various parts of the world.

For national projects supporting the field of nanotechnology and materials, it is extremely important from a medium- and long-term perspective to build research centers and networks of shared facilities that are designed for efficient use of expensive cutting-edge equipment, integration among different fields, and industry-academia collaboration as a mechanism for promoting innovation (integration, systematization).

2.6.1 Large-Scale Nanoelectronics Research Centers around the World

R&D centers for nanoelectronics have started to concentrate in a few sites, such as Albany Nano Tech (ANT) in the United States, IMEC in Belgium, and MINATEC in France (Figure 22). Device manufacturers, equipment manufacturers, and materials manufacturers gather at these sites, build next-generation devices, and construct an ecosystem for R&D on manufacturing processes. These sites are also used for research on advanced semiconductors, research that takes advantage of semiconductors and human resource training with cutting-edge facilities and R&D programs.

Figure 22

As of 2014, the ten major private-sector companies participating in ANT are IBM, Intel, GlobalFoundries, SEMATECH, Samsung, TSMC, Applied Materials, Tokyo Electron, ASML, and Lam Research.

SEMATECH, which is the central research institute among them, reached a new five-year agreement for research cooperation with the State of New York in 2013 and has entered the third stage of the project. Approximately 3,000 corporate employees work at ANT.

IMEC has rapidly expanded its scale and improved its facilities. It has grown into an internationally recognized nanoelectronics research institute working on commissioned projects and recently launched a bionanotechnology center to promote stem cell research and other types of research. IMEC's annual budget is approximately 320 million euro. It is also building a R&D line for 450mm-diameter wafers. According to its plan, a 450mm pilot line will be built around 2015, and lines for small-scale production will be launched around 2018. In 2013, more than 2,000 people work at IMEC. Among them, about 1,400 people are direct employees, close to 400 people are researchers from external organizations, and close to 300 people are doctoral students.

In Asia, the Suzhou Industrial Park, which has been under construction in Suzhou, China since 1994, has grown to 10 times the size of the Tsukuba Science City. In Singapore, the R&D complex Fusionopolis has completed its first-phase construction plan. Besides South Korea, China, and Taiwan, R&D activities in South Asia and South East Asia are concentrated in Fusionopolis and other such R&D hubs. In terms of R&D, presence of Japan is fading away even in the Asian region. Already, major Japanese companies are increasingly conducting their large R&D projects not at R&D centers in Japan, but at aforementioned overseas sites.

In Japan, at the Tsukuba Innovation Arena (TIA-nano), which started in April 2010, AIST, NIMS, the University of Tsukuba, and the High Energy Accelerator Research Organization (KEK) are working to create an internationally attractive nanotechnology research center that has a cooperative relationship with the Japan Business Federation. The aim is to promote growth of Japan as a producer of cutting-edge products. The core research domains at TIA-nano are six priority domains that directly lead to commercialization (nanoelectronics, power electronics, N-MEMS, nanotechnology for green solutions, carbon nanotubes, and safety evaluation of nanomaterials), and funds and human resources from industry, academia, and the government are concentrated in R&D activities. TIA-nano also has systems for prototyping and evaluating demonstration devices, sharing cutting-edge equipment for nanotechnology R&D, and promoting human resource development, as core infrastructure.

2.6.2 Networks of Shared Nanotechnology Facilities around the World

The United States, South Korea, and Taiwan strategically used government funds and built substantial infrastructure networks for advanced research. They assigned 10% to 15% of nanotechnology-related national investments to the construction of R&D centers and networks of shared facilities. As shared infrastructure, the National Nanotechnology Infrastructure Network (NNIN) and the Network for Computational Nanotechnology (NCN; funded by the national Science Foundation [NSF]) in the United States and six R&D centers in South Korea have completed their systems for charging fees and dealing with international activities. In Europe and Taiwan, too, networks of nanotechnology research infrastructure are built at the national or regional level.

The United States has substantial networks of R&D centers (a nanotechnology infrastructure network consisting of 14 research centers [NNIN/NSF] and a nanotechnology computer network consisting of seven computer centers [NCN/NSF]). Based on experiences as shared infrastructure accumulated over many years, these networks operate with about one-third of their expenditure being covered by the federal government.

In Japan, MEXT's Nanotechnology Platform project started in 2012 with a ten-year plan. Its goal is not only to increase the efficiency of publicly funded R&D investments by concentrating expensive cutting-edge equipment in certain areas and making it available for sharing, but also to promote collaborative activities among researchers from different fields by encouraging the exchange of knowledge and ideas and to provide opportunities for generating new technologies and businesses. The Nanotechnology Platform provides opportunities to users from industry, academia, and the government who try to develop groundbreaking materials and devices in three technological areas (Advanced Characterization Nanotechnology Platform, Nanofabrication Platform, and Molecule & Material Synthesis Platform). Thirty seven member facilities at 25 member institutions participate in the Nanotechnology Platform. Also, NIMS and JST are designated as central institutions in order to improve support provided by the Platform as a whole and increase the number of users. They act as coordinators, connecting the Platform and potential users including young researchers in Japan and local small and medium-sized enterprises.

Because of the Nanotechnology Platform network, there have been cases where even if a user could not have an issue solved by one center, the user was referred to another center in the network, allowing the issue to be solved. This is a mechanism unique to Japan and cannot be found overseas.

2.6.3 Bridging Basic Research and Commercialization in Bionanotechnology

Japan's weaknesses in commercialization in bionanotechnology are as follows: (1) medical devices are high-variety, low-quantity products, and except for a few examples, their business viability is low because the size of their market is small; (2) there are few Japanese medical device companies that can tolerate the high risk associated with advanced medical devices and that have the necessary capabilities to develop such devices; (3) product development made possible by investments in startup companies, as seen in Europe and the United States, followed by purchase and commercialization by major companies is not actively conducted; and (4) the cost of obtaining permissions and licenses is higher in Japan than in Europe and the United States because of laws and regulations.

There is thus an irony that even though the level of basic research at universities and other institutions is high, it does not lead to its ultimate goal, that is, making contributions to medicine or society.

However, many institutional improvements have been made: amendments to the Pharmaceutical Affairs Act; examination of low-risk biomaterials conducted by third-party institutions; preparation of guidelines on approval standards applied to advanced medical technologies including technologies used in regenerative medicine; prioritization of technologies to be reviewed; and deregulation pertaining to medical treatments that are partially covered by insurance. However, policy implementations for other issues have been limited. As for the second and third weaknesses listed above, there have been measures in recent years that provide public funds to encourage universities and other research institutions to cooperate with small and medium-sized enterprises to extend and commercialize technological seeds first developed in universities. However, although such direct support is effective for technologies that are potentially highly viable in the market, other technologies do not ultimately reach the commercialization stage, making it impossible to recover invested funds. To promote commercialization of domestically produced medical devices, it is necessary to make improvements to deal with the low business viability of medical devices. If the business viability of products is low because of the small size of the domestic market, it is necessary to expand their market by lowering barriers to entering overseas markets. Also, lowering commercialization costs requires efforts such as streamlining requirements concerning trial data used to apply for approval, providing support for obtaining approval, and offering free application-related consultations both domestically and internationally.

For example, considering clinical use for cancer treatment, the U.S. National Cancer Institute accepts nanoparticles and other materials and provides free basic evaluations of their in vitro/in vivo biological reactions. If some entity can offer free basic evaluations of products to enable judgment of whether their medical application is possible, such service would promote commercialization of medical products.

2.6.4 Strategies for Standardization of Nanotechnology and Research on Safety Evaluation (EHS, ELSI, Social Acceptance)

Advances in nanotechnology and materials technology, health and environmental effects of new materials and new products produced through the commercialization of such technologies, and evaluation and control of risks associated with the novelty of these products are treated as international issues. Research on the safety of nanomaterials requires a large amount of resources because some of them have nanostructures that are different from traditional materials and thus possess new physical properties. Therefore, such research is conducted under a national framework. Risk assessment research has been mainly concerned with public welfare policy (EHS: Environment, Health and Safety) as well as ethical and social issues (ELSI: Ethical, Legal and Social Issues), but in recent years, emphasis has been put on strategic efforts whose goals include commercialization. Many countries have considered national nanotechnology policies as measures for creating new markets and increased employment, which are the keys to future industry. Ensuring the safety of nanotechnology has been part of public welfare policy, which is intended to alleviate concerns of society about public welfare. However, in recent years, Europe and the United States have shown their intention to create international standards concerning the safety of nanotechnology and strategically maximize their own interests in order to ensure that society receives the benefits of nanotechnology.

It is becoming clear that Europe and the United States intend to link safety assessment of nanotechnology with safety standardization and strategically utilize it in trade. This is not a new policy, but is considered to be an extension of Registration, Evaluation and Authorization of Chemicals (REACH; chemical product regulation) in Europe and the Restriction of Hazardous Substances (RoHS) Directive. In an increasing number of cases, nanomaterials are subject to registration systems for chemical substances.

The United States has made nanomaterials the subject of premanufacture notices (PMNs) and created a significant new use rule (SNUR) under the Toxic Substances Control Act (TSCA). Whether or not a nanomaterial is treated as a new material depends in principle on its molecular identity (molecular structure). In some cases, a carbon nanotube is considered distinct if it is produced by a different manufacturer or a different process. With regard to the Globally Harmonized System of Classification and Labeling of Chemicals (GHS) of the United Nations, discussions have begun about its applicability to nanomaterials.

The OECD started the Working Party on Manufactured Nanomaterials (WPMN) in 2006. Its purpose is to promote international cooperation regarding human health effects and environmental protection issues that are related to nanomaterials used for industrial purposes. The WPMN administers nine steering groups (SGs).

Studies and investigations concerning the risk of nanomaterials and social acceptance have also been conducted in Japan. In 2005, under a project entitled Investigative Research on Increasing Social Demand for Nanotechnology, which was funded by the Special Coordination Funds for the Promotion of Science and Technology, research institutes that belonged to METI, MEXT, MOE (the Ministry of the Environment), and

MHLW (the Ministry of Health, Labor, and Welfare) cooperated, examined a wide variety of fields, and published a report of policy recommendation. Scientific research into the effect of nanomaterials on human health funded by the MHLW started in 2013, and multiple research groups have worked on the project. In addition, from 2006 to 2011 NEDO had a project entitled Research and Development of Nanoparticle Characterization Methods, which was aimed at developing techniques for preparing nanomaterial samples and performing relevant measurements and to evaluate risks. The R&D efforts continue under the project entitled the Ultralight and Strong Innovative Integrated Materials Project for a Low Carbon Emission Society: Development of Innovative Methodology for Safety Assessment of Industrial Nanomaterials. At the national level, during a period from 2007 to 2010 (under the Third Basic Plan for Science and Technology) the Cabinet Office's project entitled Promotion of R&D on Nanotechnology and Infrastructure Development Related to Social Acceptance was conducted as a cooperative measure by multiple government agencies. However, this cooperative project was not continued in the Fourth Basic Plan.

2.7 Future Prospects and Issues Facing Japan

This section discusses what role nanotechnology and materials can play in different areas in order to solve social issues that are currently facing Japan.

The Environment, Energy, and Social Infrastructure

Because of the accident at the Fukushima Daiichi Nuclear Power Plant in 2011, renewable energies such as solar power and wind power will become increasingly important in the long run. For solar power generation, development of high-efficiency solar cells and next-generation batteries will be needed; for wind power generation, development of strong, lightweight composite materials will be needed. For short- and medium-term solutions, we have no choice but to hope that thorough efforts will be made to increase the efficiency of fuel-combusting power generation based on, for example, combined-cycle operation and high-temperature combustion operation. For high-efficiency fuel-combusting power generation, it will be important to develop high-temperature-resistant materials and coating materials for increasing combustion temperature.

As CO_2 capture and storage (CCS) technology advances, it will be possible to create hydrogen from fossil fuels without emitting a large amount of CO_2 into the atmosphere. As the development of fuel cells advances, the use of hydrogen fuel, the ultimate clean energy source, is expected to gradually increase in the long run.

From the standpoint of energy saving, development of the following will be needed: solid-state lights, low-power-consumption electronics systems, high-efficiency power electronics products, thermal insulation materials, low-friction materials, strong lightweight composite materials, and thermoelectric devices that generate electric power from waste heat. However, it will be more important than anything to reexamine our lifestyle, taking the adoption of these advanced technologies as given, and to shift to an energy-saving lifestyle making full use of ICT.

To protect the natural environment, it is necessary to develop various environmental sensing systems and install them around us. Looking at the world, one sees that the amount of drinking water is limited. Urgent issues therefore include generating drinking water from seawater; cleaning water containing radioactive or toxic substances, which results, in large amounts, from shale gas production; and developing low-cost mass-producible adsorbents and purification membranes.

These social or technological issues concerning the environment and energy should be solved through interdisciplinary approaches and cooperative efforts of experts from multiple technological fields. It is hoped that R&D based on nanotechnology will play a central role.

Health and Medical Care

The recent progress in the life sciences is remarkable. It will be possible to integrate an enormous amount of accumulated knowledge on the lifescience, cutting-edge semiconductor technologies, and electronic and optical technologies by equipping semiconductor chips with organism-derived substances, such as DNA, protein, and cells, and by precisely measuring and accurately manipulating such substances. There are high hopes for innovations resulting from such integration.

From the standpoint of rising medical expenses and health management, there are high hopes for achieving highly sensitive detection of biomarkers indicating certain diseases by use of semiconductor chips. Incorporation of semiconductor chips capable of highly sensitive detection into ultra-small wearable devices enables daily health monitoring and leads to advances in the preventive medicine. If the range of detectable objects expands to pathogens such as viruses, it would be possible to build a system that constantly monitors pathogens existing in various environments and prevent infectious diseases from spreading.

For integrated devices to be utilized in actual medical practice, it is necessary to develop devices capable of both sample pre-processing and substance detection. Recent research explores the possibility of placing DNA, a single cell, or a single molecule on an artificial microstructure (or even nanostructure), such as a microfluidic channel created using microfabrication technology, and applying the ability to detect and identify the DNA and other biomolecules to diagnosis and medical treatment. As these techniques add new value to semiconductor chips, they can provide great opportunities for the semiconductor business.

There is also a research intending to utilize nanoparticles as transporters in DDSs and to perform medical treatment by efficiently delivering drugs to areas affected by a disease. Nano-DDSs are considered essential for practical use of nucleic acid medicine. It is therefore necessary to conduct R&D on the material design of nanoparticles whose pharmacokinetics and intracellular behavior can be controlled. It is hoped that nano-DDSs carrying a drug and a sensitizer for bioimaging will be clinically applied as a technology realizing integration of diagnosis and treatment. Also, combination of a nano-DDS and physical energy, such as light, ultrasound, and a neutron beam, enables minimally invasive treatment.

Since the discovery of iPS cells, there have been high hopes for their application to regenerative medicine and screening in drug discovery, which will lead to personalized medicine. Inducing iPS cells to differentiate into a desired tissue requires a scaffolding material. It has been made clear that the mechanical properties and minute shapes of the material contacting the cells affect their growth and differentiation. This fact is expected to provide new methods to culture and manipulate cells. Technologies to form cell aggregates that have complex structures and functions are quite important for not only regenerative medicine but also drug discovery. It is therefore necessary to conduct R&D on materials and devices needed for such technologies. Here, too, integration of materials science and the life sciences is needed. Connecting such integration to innovations in diagnosis, medical treatment, and drug discovery is an important challenge in medicine. Also, from the standpoint of patients' quality of life, many of the medical materials that have already been put to clinical use require improvement. Further development efforts are thus needed.

Information, Communications, and Electronics

The IoT requires ultra-small inexpensive chips that are equipped with various sensors and communication capabilities. Since these chips are embedded in objects that we use daily, they need to be equipped with ultra-small batteries that power them or with energy-harvesting technology that converts various energy sources in the environment into electric energy. The IoT is expected to help people lead healthier and more comfortable lives and also to create a safer and more secure society by providing measures for preventing disasters and crimes. In realizing such a society, nanoelectronics are expected to play an important role. Advances in nanoelectronics are considered to occur in phases: pursuit of extreme miniaturization of devices (focus on ever-smaller nanoscale realms); emergence of multiple functions based on introduction of new materials together with many functions produced by light, spin, biology, and MEMSs (integration of nanotechnologies); application of nanotechnology to high-definition displays, wearable devices, and the IoT (System Nano).

Among various nanotechnologies, nanoscale thermal control is important. At the nanoscale level, electrons, spin, photons, phonons, and so forth, which are quantized, play an important role to produce various functions. In terms of application of nanotechnology to various devices, device performance is significantly restricted by the heat generated by electrons moving through channels, as seen in micro-CMOS devices. In addition, many different kinds of materials are used in the microstructure of semiconductors, leading to complex phonon transmission. There is thus a risk of creating hot spots in the devices. Thermoelectric devices, which convert heat into electric energy, require simultaneous control of flows of electrons and phonons. Improvement of the performance of thermoelectric devices depends on how mutually conflicting transport requirements are resolved by the structural design of the devices. Also, for heat-assisted magnetic recording, which is a highly anticipated technology in next-generation magnetic storage devices, thermal control of nanosecond order in the nanoscale region must be achieved along with spin control in microscopic magnetic domains. For these reasons, nanoscale thermal (phonon) control, which we call "phonon engineering", is important in applications. What are needed today are comprehensive design methods for nanoscale structures that take into account factors such as electrons, spin, photons, and phonons.

Materials and Manufacturing

Advances in information and communications technology have the potential to significantly change R&D related to nanotechnology and materials technology. As improvement in the performance and reliability of devices is pursued, materials supporting these qualities are becoming more complex and diverse. At the same time, necessary functions must be realized by combining chemical elements that abundantly exist in nature. However, the number of combinations of relevant materials is enormous, which makes it difficult to search for or develop materials based on traditional experimental or theoretical approaches. Due to dramatic improvements in the performance of computers and advances in information technology, it is becoming possible to discover systematic rules concerning the performance and functions of materials based on large-scale data on materials (which deserved to be called big data) and to develop materials efficiently within a short period of time.

Accelerating this trend requires not only cutting-edge information technology that enables researchers to rapidly organize enormous amounts of data on materials using computers, to search for necessary information, and to discover new knowledge, but also researcher groups who fully utilize these tools and develop new materials. Such a field is called Materials Informatics. R&D centers that gather researchers and the necessary tools must be created to maintain and strengthen capabilities to develop materials that have been a source of industrial competitiveness of Japan.

There are efforts, mainly in Europe and the United States, to re-establish manufacturing technologies. In the United States, there are actions that are calling for reshoring factories from overseas locations as energy cost fell due to the emergence of shale gas. Also, new manufacturing models for the new era of information and communications technology, which are referred to as the Industrial Internet in the United States and Industry 4.0 in Germany, have been introduced. Dramatic performance improvements in computers have led to expanded possibilities for simulation technologies that, along with advances in materials informatics, are expected to lead to innovations in design technology in manufacturing. One example is progress in 3D printing technology based on the intensive use of computers. With digital 3D information on the shape of an object to be manufactured and a 3D printer, anyone can produce an object with the same shape, even a complex one. There are hopes for new developments in manufacturing that are based on proper matching of various materials, flexibility in design based on computers and 3D digital information, and advances in printing equipments.

In manufacturing, there will be a shift in focus from the large amounts of energy and resource consumption of the past to small environmental burdens and human-friendly products exemplified by biomimetics. In biomimetics, researchers study the structures, functions, and production processes of organisms and apply them to new manufacturing technologies. It is an integrative field between biology and engineering (nanotechnology and materials, mechanical, and electrical engineering) that can potentially bring innovations to many areas including robotics technology and medical technology. Systematic efforts based on collaboration among researchers in biology and the field of nanotechnology and materials are necessary in biomimetics.

Examples of Challenges in Nanotechnology and Materials

The following discusses the main challenges that Japan should tackle in the field of nanotechnology and materials.

(1) Materials and Membranes with Separation/Adsorbent Capabilities

Developing materials and membranes with separation/adsorbent capabilities is the key in the following wide range of areas: removal of environmental pollutants; energy-efficient separation in chemical processes; separation and storage of hydrogen for the coming "hydrogen society"; and medicine. It is necessary to actively work on new materials, such as porous materials and nano-carbon materials, to clarify material characteristics appropriate for different uses, and to conduct R&D on practical, functional materials and membranes.

(2) Interactive Biological Interfaces

It is desired to combine organism-derived substances, such as cells, protein, and DNA, with devices created based on semiconductor technology, microfluidics technology, and electronic/optical technology, to understand and control their dynamic behavior, and to apply relevant techniques to regenerative medicine, diagnosis, and screening in drug discovery. To achieve these things, it is necessary to meticulously design and create biological interfaces of devices and develop interactive biological interfaces that are capable of interacting with cells and other organism-derived substances at the molecular level.

(3) Wearable/Implantable Electronic Devices

It is expected that objects around us will have computing functions, and that we are moving toward the era of the IoT in which these objects exchange information with one another. In such a world, it is necessary to equip ultra-small low-cost semiconductor chips with nanoelectronic functions (e.g., sensing, networking, and energy-harvesting functions) and to create wearable or implantable electronic devices.

(4) Bio-Inspired, Digital, and Nanofabrication Technologies.

Completely novel manufacturing techniques can be developed by studying the structures, functions, and production processes of organisms and making full use of cutting-edge manufacturing technologies like computer-assisted design technology and 3D printing (as well as materials informatics and large-scale simulation). This reflects the importance of technologies used in manufacturing. It is therefore necessary to conduct R&D on bio-inspired manufacturing technology, materials science, and microrobotics.

(5) Device Innovation Based on Electrons, Photons, Spin, and Phonons

Establishing next-generation nanoelectronics technologies require overcoming challenges that are characteristic of the era of device microfabrication: developing technologies for controlling heat (phonons) at the nanoscale level; combining the resulting technologies and existing design/control technologies related to electrons, spin, photons; developing unified design technologies for electrons, spin, photons, and phonons, which can be described quantum mechanically as particles and waves.

(6) Data-Driven Material Design (Materials Informatics)

Efforts to pursue highly functional, highly reliable, low-cost materials have become increasingly complex and multifaceted. To maintain and improve Japan's industrial and technological competitiveness, it is necessary to develop new approaches in which the search for and development of materials are made efficient by utilization of enormous amounts of data on materials.

Creating a Platform for Innovation in Nanotechnology and Materials

In addressing global issues, it is vital for Japan to maintain and strengthen its R&D capabilities in the nanotechnology and materials field, which is a source of the county's industrial competitiveness. Therefore, Japan needs to create an environment throughout the country that will enable it to maintain its world-class fundamental technologies for nanotechnology and materials science, to give academia and industry easy access to them, and to produce innovations that will lead to practical applications and commercialization. To observe nanoscale phenomena using nanotechnologies and to understand and control those phenomena, sophisticated, expensive equipment is required as well as highly specialized engineers to operate it. Also, understanding such phenomena requires not only simulations at an enormous computational scale, but also schemes that organize and synthesize a vast amount of resulting information and make it possible to acquire new knowledge. Such a process requires the following factors: supercomputers for high-speed simulations; a nanotechnology platform that enables measurement, processing, and synthesis of materials; and informational infrastructure for materials development that manages and provides vast quantities of data on materials. It is urgently needed to build a platform for innovation in nanotechnology and materials that enables these factors to not only operate locally but also closely cooperate with one another as a whole system. It is hoped that such a platform functions as a portal for overseas researchers to learn about nanotechnologies and material technologies developed in Japan and as a place for exchanges among researchers. Also, similarly to the case of MEXT's Nanotechnology Platform, this proposed platform should create regional satellite research centers to enable local researchers to have informational access to cutting-edge technologies nation-wide and easily exchange ideas with other researchers. Such regional centers are also expected to contribute to vitalization of regional industries.

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