CRDS-FY2017-XR-02

Nanotechnology and Materials R&D in Japan (2018): An Overview and Analysis

March 2018

Center for Research and Development Strategy
Japan Science and Technology Agency

Executive Summary

Nanotechnology and materials continue to evolve with such core technologies as control of nanometer-scale structures, high-resolution microscopes with a sub-Ångström resolution, prediction of material structures and functions using the first-principle calculation, and characterization of materials using simulation and modeling. They are expected to provide a cross-cutting technology with life sciences and clinical medicine, energy and environment, social infrastructure, and information and communication.

Nearly fifteen years have passed since national policies on nanotechnology were initiated in many countries. During these years nanotechnology has been caught up in the pursuit of technological limits, technology fusion, and systemization. Since 2010, in particular, there has been an emphasis on the fusion of different technologies and systemization aimed at industrialization and social implementation. According to a report issued by Lux Research Incorporated, the market size of new products commercialized by nanotechnology (nano-enabled products) expanded rapidly from US$850 billion to US$1.6 trillion during the two years between 2012 and 2014. Today, nanotechnology is widely used not only in R&D fields but also in diverse commercial products and various industries.

In the United States in-depth discussions were conducted in 2016 to review the National Nanotechnology Initiative (NNI), the world's first national program to coordinate multiagency efforts in nanoscale science, engineering, and technology. The review led to the conclusions that collaboration among all industrial sectors is required to commercialize knowledge and technologies generated by the R&D investments in nanotechnology and that the dissemination of the knowledge and technologies, Environment, Health, and Safety (EHS) of products using nanomaterials, and Ethical, Legal, and Social Issues (ELSI) of nanotechnology should be made public. It was also concluded that the commercialization of nano-enabled products should be promoted through these actions and that the economic benefits should be provided to the general public. It is now being carefully watched whether these conclusions are kept or changed from 2017 under the new US government. In the meantime, a new technological framework, Horizon 2020, launched in Europe positions nanotechnology and advanced material technology as one of the key enabling technologies (KET's). A future image of autonomous driving systems has been raised as a symbol of the integration of elemental technologies of nanotechnology and materials. In such Asian regions as China, Taiwan, Korea, and Singapore, R&D facilities for nanotechnology were established to attract the world's R&D. In particular, we can see that China's huge R&D investment in this field is reflected in the recent rapid increase in academic papers.

When we turn our focus to industrial trends, we see that the concept of Industry 4.0 was launched in Germany, and that ICT-related technology such as IoT or AI are greatly influencing the society and economy worldwide. Devices and component materials, which

will play a key role in the coming IoT/AI era, would be made of a lump of nanotechnology. IoT devices embedded in the products of our surroundings possess capabilities of various sensing, computing to process collected data, networking to communicate data with the cloud, and energy-harvesting to acquire the electric power needed to drive themselves on-site when needed. Real-time information processing and actions are required in the automobiles and robots entering our lives. Massive data processing technologies are also required to reduce load on the network in the IoT device side. In these situations, high computing capability including AI will be incorporated in the IoT. AI is also expected to exert its power in various fields, such as massive image, voice, and video data processing, natural language processing, optimization, and inference, which are difficult to achieve with conventional computers, and thus to work as an accelerator to complement conventional computers. New algorithms exceeding the potential of the von Neumann architecture and hardware to execute the new algorithms are highly sought worldwide, and the progress of nanotechnology and materials is expected to provide the way to fulfill those requirements. As semiconductors reach their limit in miniaturization, the need for a new technology playing a substantial role in the post-Moore era is widely recognized. Neuromorphic computing incorporating the mechanism of ultra-low energy computing executed in a biological system including a human being and quantum computing operating under the principle of quantum mechanics and providing the solutions for optimization problems that are difficult to solve substantially with present computers are candidates to provide the new technology. The progress of nanotechnology and materials is highly expected to implement those computing schemes as devices.

On the other hand, the progress of information technology for utilizing big data has begun to influence the methods of R&D on nanotechnology and materials. The accumulation of massive experimental data generated newly and renewed continuously enables the discovery of knowledge on new materials and the efficient design, search, and development of materials with desired characteristics. In order to make this possible, the fusion of material technology and advanced information technology is needed, and a new approach to material development called data-driven material design (Materials Informatics) is being initiated worldwide. The recent increase in computing power dramatically expands the potential of computer simulations for designing and developing materials, components, and even complex systems. Multi-scale simulations for consistently designing macro-scale complex systems approaching final products from the beginning of nano-scaled material structures governed by quantum mechanics are becoming feasible. Furthermore, 3D printing technology for manufacturing target structures flexibly based on this digitalized design data is making rapid progress, and progress in information technology is bringing about a revolution in various aspects of manufacturing including nanotechnology and materials.

In the previous panoramic view report on the nanotechnology/materials field in 2015, slightly more emphasis was placed on nanotechnology applications in the energy and environment areas, as well as the life sciences and medical areas. In this 2018 version, the direction of nanotechnology and materials for driving the IoT/AI era is described together with a new technical description on structured materials, sensing technology, and bonding and adhesive technologies used for social infrastructures. An overall perspective of the R&D trends both inside and outside Japan and their prospects, and Japan's issues and grand challenges particularly in the field of nanotechnology and materials are summarized comprehensively based on the information gathered through the related workshops held at Center for Research and Development Strategy (CRDS) and interviews with professionals. The panoramic view of nanotechnology and materials was reviewed and revised, and 37 major R&D areas were extracted. Moreover, ten Grand Challenges were identified in the field. This report describes CRDS's comprehensive views on nanotechnology and materials produced by collecting information and opinions through discussions in workshops and with the collaboration of 240 professionals from industry, academia, and government.

Outlook for R&D on Nanotechnology and Materials	
Global trends in technological innovation	✓ Advanced nanotechnologies are used in devices and component materials that play a key role in the coming IoT/AI age ✓ For hardware, advanced nanotechnology is being implemented in innovative computing and new architectures that will influence competition in edge/cloud AI, IoT sensors, self-driving vehicles, robots, mobile devices, energy-converting devices, and diagnostic/therapeutic devices ✓ Major trend toward new materials for this hardware from data-driven materials informatics, but a winner has yet to emerge ✓ There is a trend toward integrating individual nano-component technologies developed over the past 15 years or so to create products and systems that are beginning to permeate the market ✓ The market for products developed with nanotechnology (nano-enabled products) grew to US$1.6 trillion (doubling between 2012 and 2014; Lux Research Inc, 2014)
Japan's status	✓ In Japan's industrial configuration, more weight has been placed on the raw materials industry in recent years ✓ Historically, Japan has been strong in materials discovery and design technologies such as elements strategies and characterization of materials, molecular technologies, battery materials, electronic materials, power semiconductors, and structural materials ✓ Moreover, Japan is strong in measurement assessment, analysis, and quality control used for such technologies ✓ These strengths are advantages for popular technologies that are energy-saving and have low environmental impact ✓ Yet, Japan is not strong in computation and data science; software, standardization, and regulation strategies; medical apps; horizontal/industry-academia collaboration; ELSI/EHS on nano/new materials; K-12 education and communication
Challenges	✓ Integrating dissimilar fields: profound R&D and both horizontal and vertical collaboration ✓ Cross-ministerial and industry-academia collaboration: eliminating the time gap between R&D phases → creating an ecosystem of advanced R&D and trial commercialization ✓ Establishing ten Grand Challenges at CRDS

Figure 0. Outlook for R&D on Nanotechnology and Materials in this report

Contents

1. Purpose and Structure of This Report

1.1 Purpose

Center for Research and Development Strategy (CRDS) was established in 2003 as an affiliated institution of Japan Science and Technology Agency (JST) in order to independently carry out investigation and analysis and make proposals on science, technology and innovation (STI) policy. CRDS aims to be the think tank leading the advancement of science and technology as well as the creation of innovation for the purpose of the sustainable development of Japan and human society.

CRDS follows, overviews and analyses the trend of society, STI and their relevant policies in Japan and abroad. Based on the above, CRDS extracts problems to be tackled, proposes STI policy and/or research and development strategy and works to bring them into reality. CRDS bears in its mind, while carrying out its duty, that it should cooperate and exchange opinions with private, public and academic sectors as well as general stakeholders in the society, and further with foreign relevant institutions. CRDS surely makes public the result of its activity.

This Overview Report is an intellectual asset produced with the aim to widely share information in the field of nanotechnology and materials with stakeholders engaged in STI. 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: 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. Chapter 3 provides, from several perspectives, clear overall pictures of the history, current state. Chapter 4 shows the future direction and challenges of relevant fields.

2. Overview: The Field of Nanotechnology and Materials

2.1 Scope and Structure of the Field

Nanotechnology and materials continue to evolve with such core technologies as control of nanometer-scale structures, high-resolution microscopes with sub-Ångström resolution, prediction of material structures and functions using the first-principle calculation, and characterization of materials using simulation and modeling. They are expected to provide a cross-cutting technology with life science and clinical medicine, energy and environment, social infrastructure, and information and communication. The following is an overview of research being conducted on nanotechnology and materials, covering facts observed around the world including technological advances, national plans and investment strategies, and research potential. 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.

2.1.1 Definition and Characteristics

- Definitions and Characteristics of Nanotechnology

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

Nanotechnology An academic or technological field to fabricate 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 to apply or combine these factors with other knowledge and technology.

Integration among different fields is the most important characteristic of nanotechnology, by which new technological fields can emerge. To be more precise, the academic aspects of the field should be called nanoscience and the technological aspects 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-, and two-dimensional carbon nanostructures, respectively. In recent memory, rotaxanes were used to construct “molecular machines,” for which the Nobel Prize in Chemistry was awarded in 2016. Shifting focus to the realm of biotechnology, biological materials 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 produced 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) a nanoscale surface/interface effect generated by an increase in the ratio of the number of atoms at the surface/interface of a material to the number of atoms inside the material. These factors lead to nanoscale physical properties that completely differ from ordinarily observed physical properties. A future focus of attention will be on various transport phenomena involving electrons, photons, phonons, ions, molecules, and spin confined in nanostructures designed and incorporated into materials. Techniques to realize and control such phenomena are expected to become essential for implementing the IoT devices, which will provide a great impact not only in the industrial area, but also in the areas of energy, life sciences, and medical care.

• Definition and Characteristics of Materials

In this report, we define materials as matter that possesses 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.

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

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

3. Organic and polymeric materials: materials consisting of carbon as the main element as well as oxygen, hydrogen, nitrogen, etc. Examples include fibers and plastics made of polymer compounds, organic electronic materials such as organic electroluminescent materials, and supramolecular assemblies and gels that employ self-assembly properties.

4. Biological materials: materials that make up organisms. Main examples include proteins, nucleic acids, and carbohydrate chains.

Materials can be broadly classified as either organic matter (including biological materials) or inorganic matter (including metallic materials). In recent years, we have seen the emergence of many hybrid materials and composite materials, such as carbon-fiber-reinforced polymers, that combine both organic and inorganic materials to obtain desired functions and properties. The combining of such materials is an area of great interest in R&D, owing to its potential for producing new materials with unprecedented functionality.

2.1.2 Social Expectations for Nanotechnology & Materials and Issues Toward their Realization

The field of nanotechnology and materials plays a role in providing fundamental technologies for use in a wide range of application fields, including information, communications, and electronics that drive the IoT/AI age; manufacturing; energy and the environment; and health and medical care, and contributes to technological innovation through integration with these applied fields.

● Information, Communications, and Electronics Driving the IoT/AI Age

Through radical advances in information and communications technology (ICT), technologies such as the Internet of Things (IoT) and artificial intelligence (AI) are beginning to have enormous social and economic impacts. Diverse information necessary for providing services to users is collected through IoT, and vast amounts of the collected information (big data) is transmitted to the cloud over a network. AI is then employed to analyze big data in the cloud in order to produce new knowledge that can provide high added value for developing diverse businesses in the real world. This will achieve more integration between cyber and physical worlds in such areas as automobiles, home appliances, medical and health-related equipment, factories, finance, and energy networks, as is conceptually illustrated in Figure 1, leading to a new era that is being called a super-smart society, or Society 5.0.

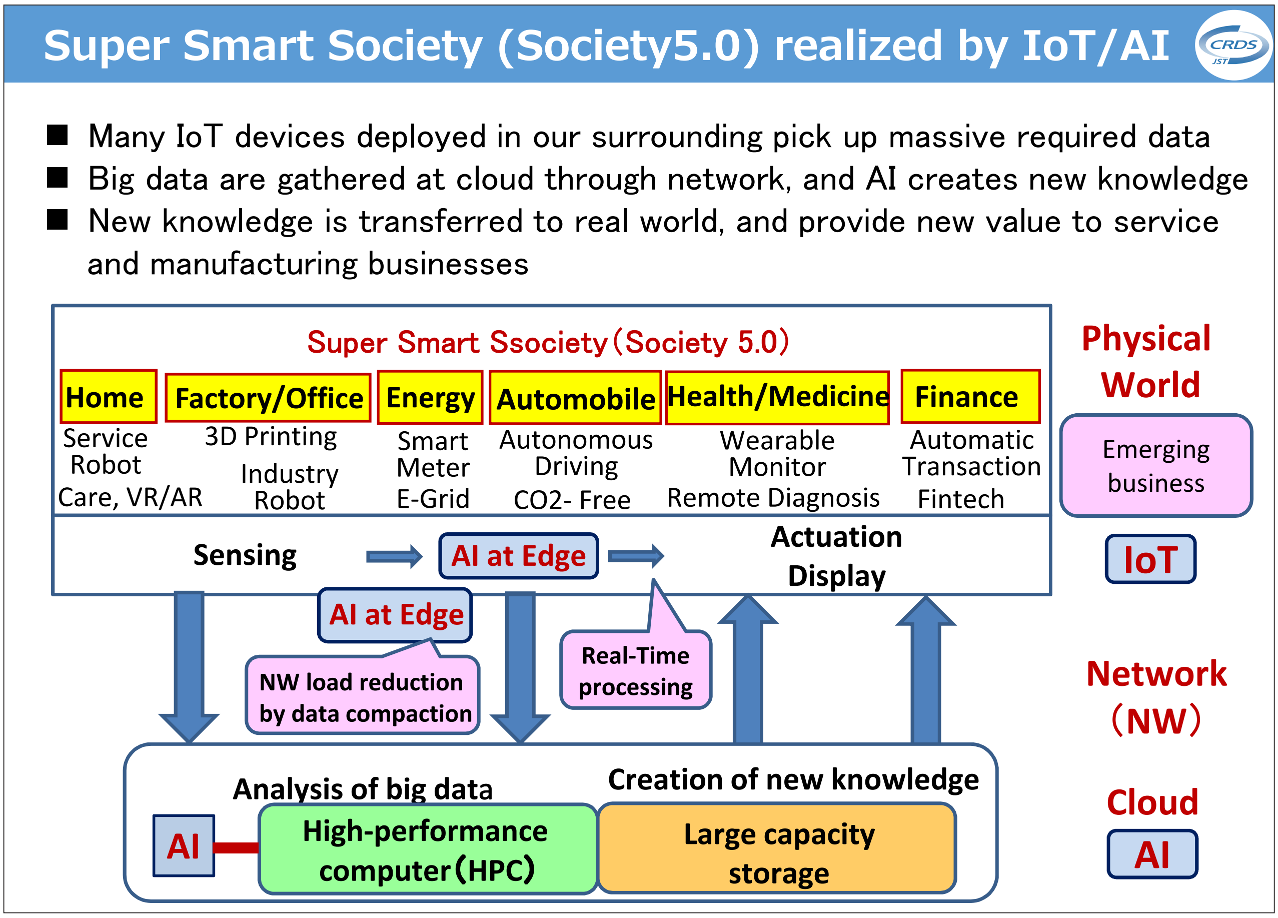


Figure1. Super Smart Society (Society5.0) realized by IoT/AI

IoT devices embedded in items we use in our everyday lives possess various sensing functions, network connectivity for transmitting data to the cloud, and, depending on its application, energy-harvesting for producing on site enough power to sustain its own operations. Robots and automobiles, for example, must be capable of processing data and taking actions in real-time. In some cases, massive volumes of data must be processed in advance to reduce load on the network. At these times, the IoT devices may be equipped with advanced computing functions that include AI. AI is also expected to exert its power in various fields, such as massive image, voice, and video data processing, natural language processing, optimization, and inferring which are difficult to implement on conventional computers, and thus to work as an accelerator to complement conventional computers. As witnessed with the computer program AlphaGo developed by Google DeepMind, AI has reached the capability for defeating a world-class Go player. Here, tensor processing units (TPU) are used to perform advanced computations on data received from graphics processing units (GPU) according to machine learning algorithms, such as deep learning and reinforcement learning. The demand for AI capabilities in these areas shows no sign of abating, with increasingly high hopes for new algorithms that exceed the potential of the von Neumann architecture and hardware for implementing the new algorithms. Possible candidates for meeting these needs include neuromorphic computing incorporating the mechanism of ultra-low energy computing executed in a biological system, and quantum computing operating under the principle of quantum mechanics and providing solutions for optimization problems that are intrinsically difficult to solve with present-day computers. Technologies such as sensing, networking, and computing will be essential to support a super-smart society, and nanotechnology and materials centering on nanoelectronics is widely expected to make these technologies a reality.

- Transformation of Material Development and Manufacturing with Information Technology

At the same time, advances in information technology that take advantage of big data are expected to have a significant effect on development in nanotechnology and materials. Massive data sets on materials that are updated and receive new entries on a daily basis enable the discovery of information about new materials and the efficient exploration and development of materials with desired properties. To achieve this, the fusion of material technology and advanced information technology is needed. A new approach to material development called data-driven material design (Materials Informatics) has been introduced in Japan's Cabinet Office, Ministry of Education, Culture, Sports, Science and Technology, and Ministry of Economy, Trade and Industry(*) and is eliciting much anticipation for future developments. The recent increase of computing power dramatically expands the potential of computer simulations to design and develop materials, components, and even complex systems. It is now possible to conduct multi-scale simulations for coherently designing everything from nanoscale structures governed by quantum mechanics to macro-scale complex systems approaching end-products. Considerable progress is also being made in 3D printing technology with flexibility to produce target structures based on this digitized design data, and advances in information technology are expected to revolutionize manufacturing technology as a whole, including the manufacturing of nanostructures.

(*) Cabinet Office: Materials Integration in "Structural Materials for Innovation" of SIP
http://www.jst.go.jp/sip/dl/k03/jst_pamphlet_english.pdf
MEXT: "Materials Research by Information Integration" Initiative, a JST project for supporting the creation of innovation hubs
http://www.nims.go.jp/MII-I/en/
METI: "Ultra High-Throughput Design and Prototyping Technology" for Ultra Advanced Materials Development Project
http://www.nedo.go.jp/activities/ZZJP_100119.html

Expectations on Science and Technology for Solving Increasingly Complex and Pressing Environmental and Energy Problems

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. This period saw the development of hydraulic fracturing technology 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 changing significantly. At the same time, it has been pointed out that the method used to extract shale gas causes water and soil pollution and earthquakes. With many issues to be resolved, the future of shale gas extraction is impossible to predict.

In the aftermath of the accident at the Fukushima Daiichi Nuclear Power Plant caused by the Great East Japan Earthquake of 2011, Japan has reexamined its use of nuclear power. The accident cast doubt on the safety of nuclear power generation, leading to plans to introduce more renewable energy. The operations of all of Japan's nearly 50 nuclear reactors were suspended following the nuclear accident. As of 2017, some plants have resumed operations after undergoing strict inspections by the Nuclear Regulation Authority. However, it is still not possible at this time for Japan to have much reliance on nuclear power generation, which once accounted for one-third of the country's total energy production.

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 undeniably worsening. Left unchecked, this situation will give rise to increased 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 emerging countries and developing countries continue, without exception, to drive themselves toward economic development and market expansion. The reduction of greenhouse gases is an issue that faces the entire globe and one that requires an immediate response. A related global issue is conservation of biodiversity. These issues have a significant impact on human activities.

Health and Medical Technologies Needed for Combating Rising National Medical Care Expenditure in a Super-Aging Society

All people want to lead safe and healthy lives with peace of mind. Needless to say, meeting this shared desire for quality of life (QOL) is a pressing issue for societies with rapidly aging populations. Japan is entering the era of a super-aging society ahead of all other countries. The ratio of people aged 65 or older in Japan exceeded one-fourth its total population in 2015 and is expected to reach a ratio of one-third by 2035, just twenty years later. National medical care expenditure is also increasing as a result. In 2015 national medical care cost 42 trillion yen, of which medical expenses for the elderly persons who are 75 years and over accounted for 15 trillion yen, and the same medical expenses are projected to rise to 47 trillion yen in 2020, with the share of expenses for the elderly persons increasing to a projected 20 trillion yen (Annual Health, Labour and Welfare Report 2011-2012, "Future Outlook of Medical and Related Expenses and an Estimation of the Financial Impact"). The cost of nursing care has also increased annually, rising to near 10 trillion yen in 2015.

Maintaining health requires technologies for early detection and prediction of physical abnormalities and prevention of epidemics of infectious diseases. These technologies are essential for reducing medical expenses and long-term costs. With respect to diagnosing and treating diseases, R&D has been conducted to improve the efficacy of medical interventions and the economic efficiency of health care. It will also be necessary to develop technologies for minimally invasive or noninvasive diagnosis and treatment in order to improve patients' QOL.

2.1.3 Panoramic view of the Field of Nanotechnology and Materials

The field of nanotechnology and materials is founded on nanoscience, which has developed as a study of nanoscale phenomena based on such basic sciences as materials science, quantum 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. Through this application, unique properties and functions are derived from the nanostructures of materials, and applied to devices and components that ultimately act as the engine for innovation in various fields including the environment; energy; life sciences and health care; social infrastructure; and information and communication technology (ICT) and electronics. Figure 2 provides a panoramic view of the field.

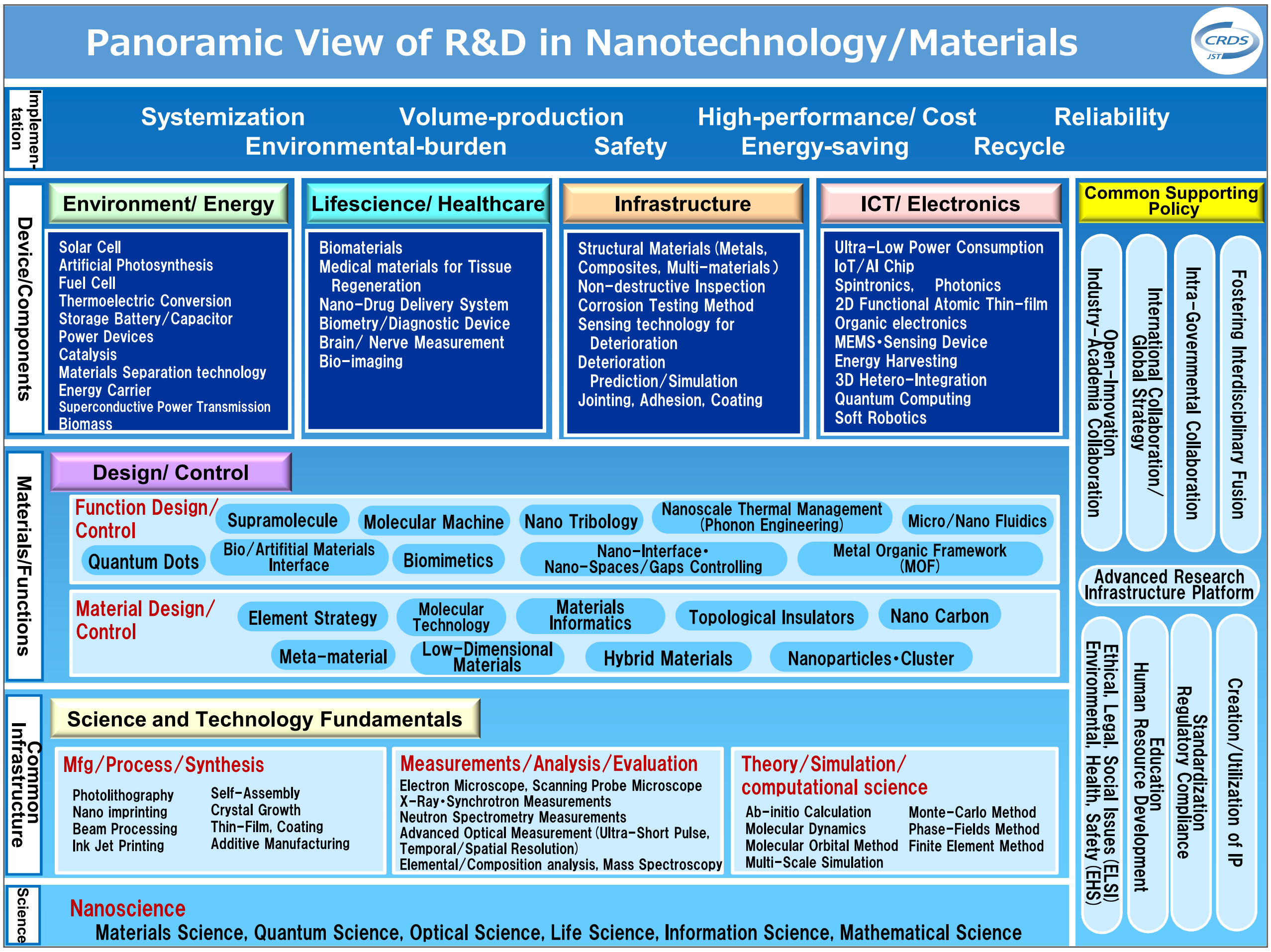


Figure 2. Panoramic view of the Field of Nanotechnology and Materials

The common foundation layer consists of technologies associated with manufacturing and processing, synthesis, measurement and analysis, theory and simulation. The upper section of this layer constitutes design and control for materials and functions that includes distinctive concepts related to nanotechnology and materials as a whole, such as element strategy, molecular technology, and materials informatics in the domain of material design and control, and nanointerface/nanospace control and nanoscale thermal management in the domain of functional design and control.

Devices and components are built by combining these materials and functions. In addition, the various devices and components are classified under the following areas according to their applications: the energy and the environment; life sciences and health care; social infrastructure; and ICT and electronics. In this figure, devices and components that belong to multiple areas are listed under the area that best represents them.

These devices and components are ultimately built into systems. Judgments are made regarding whether the market or society can accept such systems, with consideration given not only to product performance, mass productivity, cost competitiveness, reliability, and safety, but also to negative environmental impacts, energy savings, and recycling. Subsequently, the systems are introduced into society.

The right column in the figure (“Common Supporting Policies”) lists common policy issues such as measures for promoting integration and collaboration, infrastructure improvement, development of human resources, strategies on intellectual property and standardization, 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. Studying how nanomaterials affect health and the environment and how to assess and manage risk is particularly important because nanomaterials having the same molecular formula and weight can exhibit greatly different functional activity and toxicity owing to their shapes, surface conditions, and other factors. In recent years, ELSI and EHS issues have been addressed internationally as major challenges for nanotechnology.

In this report, 37 areas of R&D have been identified as key areas to keep a close eye on for at least the next ten years (Figure 3).

37 Major R&D Fields in Nanotechnology/Materials

Category	R&D Fields
Energy/ Environment	Solar cells
	Artificial photosynthesis
	Fuel cells
	Thermoelectric conversion
	Battery devices
	Power semiconductor devices
	Green catalysts
	Separation technologies
Life Sciences/ Health Care	Biomaterials
	Materials for regenerative medicine
	Nano - drug delivery system (nano-DDS)
	Measurement and Diagnostic Equipment
	Brain/neural activity measuring devices
	Molecular imaging

Category	R&D Fields
Design and Control of Functions/ Materials	Controlling Nano-micro spaces and gaps in Materials
	Biomimetics/Bio-inspired engineering
	Molecular technology
	Element strategy
	Materials informatics
	Phonon engineering

Category	R&D Fields
ICT/ Electronics	Ultra-low-power nanoelectronics devices
	Spintronics
	Atomically thin 2D functional films
	Photonics
	Organic electronics
	MEMS/Sensing devices
	Energy-harvesting
	3D heterogeneous integration
	Quantum computing
	Fundamentals of robotics technology
Social Infrastructure	Structural materials (metals/composites)
	Nondestructive testing/deterioration prediction
	Bonding, adhesion, coating

Category		R&D Fields
Science and Technology Funda-mentals	Fabrication/ processing	Fabrication/processing technologies
	Measure-ments/ analysis	Nanoscale operando observations (SPM, TEM, synchrotron/X-ray measurements, spectroscopy, etc.)
	Theory/ computation	Materials simulation
Common Supporting Policies	ELSI/EHS	Risk assessment/management, international standardization and Societal implications of nano-ELSI/EHS

Figure3. 37 Major R&D Fields in Nanotechnology/Materials

3. Analysis: History, Current State, and Future Direction of the Field

3.1 Historical Transition of the Field, The Evolution of Nanotechnology and Materials

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: "Progress Nano," "Fusion Nano," and "Systems 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 Progress Nano, which is the pursuit of ultimate nanoscale functions for component technologies (Figure 4). For example, measuring technologies have evolved from electron microscopes used to investigate crystals to scanning probe microscopes and single-molecular spectroscopic techniques targeting individual atoms and molecules. This is comparable to the techniques for observing and measuring single molecules and single cells in biotechnology. In semiconductors, miniaturization techniques for devices have broken through to the 10 nm and less region, but there is need for innovation in all component technologies involved in manufacturing, including lithography. The process of developing these cutting-edge technologies requires persistent R&D efforts along with the incorporation of new concepts.

The second stage is Fusion Nano, which initiates integration among different fields through interdisciplinary research on component technologies at the most cutting-edge level and evolves into new integrated nanotechnologies with new functions. Taking semiconductor technology as an example, a demand for thinner gate insulators was spurred on by the miniaturization of devices. However, since there is little hope of improving device performance with existing SiO_2 layers, it has become vital to develop high dielectric materials, as well as new gate electrode materials. There would likely be no expansion of LSI performance without the emergence of fusion technology combining the pursuit of miniaturization with the accompanying development and introduction of new materials. For the fields of energy and the environment, technologies such as solar cells, fuel cells, rechargeable batteries, and artificial photosynthesis are expected to play key roles in solving increasingly acute problems related to energy and global warming. Hence, while material innovation is needed, fusion technologies will be indispensable because, rather than pursuing performance enhancements for individual materials of a device, such as electrode and electrolyte materials, it will be necessary to optimize component materials for the purpose of enhancing the performance of the devices or system as a whole.

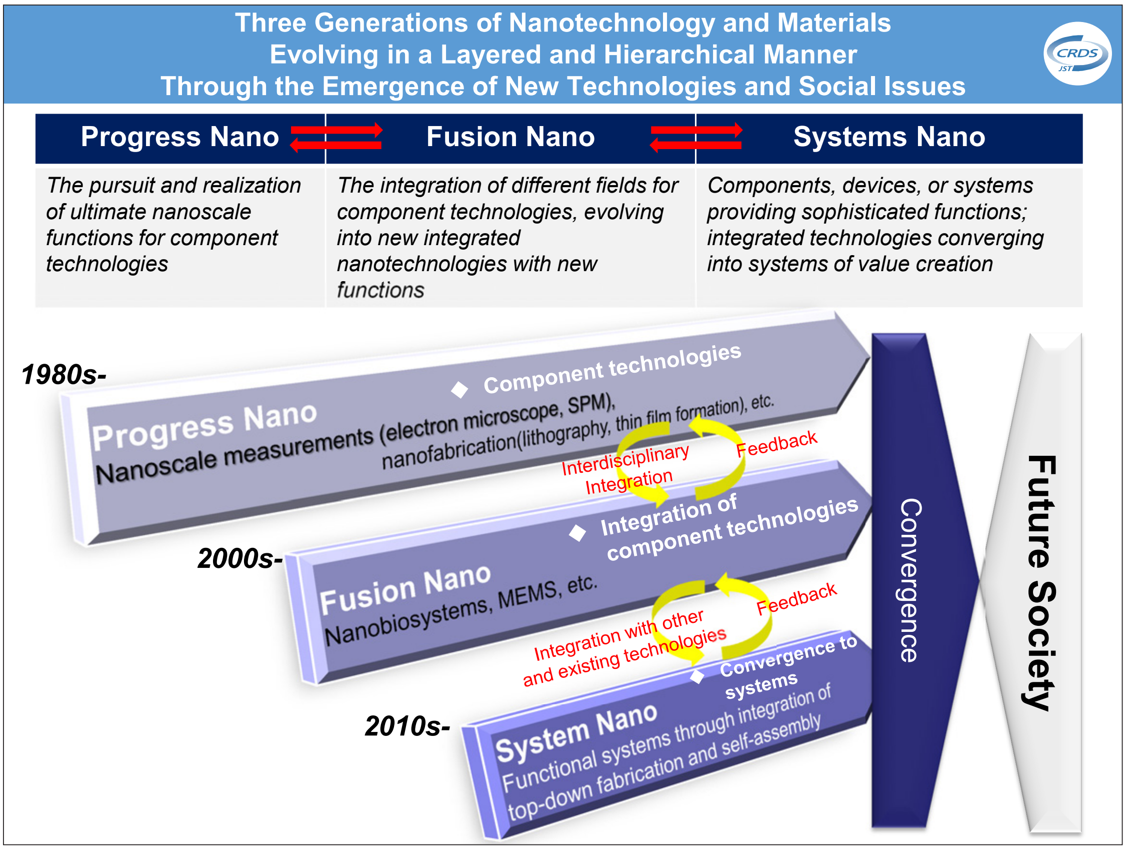


Figure4-1. Three Generations of Nanotechnology and Materials

Progress Nano	Fusion Nano	Systems Nano
The pursuit and realization of ultimate nanoscale functions for component technologies	*Integrating different fields through interdisciplinary research on component technologies at the highest level and, by combining with other technologies, evolving into new integrated nanotechnologies with new functions.*	*Components, devices, or systems with sophisticated functions for solving problems. Cutting-edge component technologies are integrated to produce new nanotechnologies and materials that converge into a system of value creation.*
ex. Measuring Technologies Evolved from targeting bulk crystals at the macroscale to SPM, aberration-corrected electron microscopy, and monomolecular spectroscopy technologies with single atom or molecule resolution. Structures revealed for the first time with these technologies will lead to design ideas for new materials.	**ex. Energy and the Environment** Solar cells, fuel cells, batteries, artificial synthesis, and gas separation will be key for these fields. Material innovation is needed, but fusion technologies will be indispensable because, more than performance enhancements for individual materials of a device, such as electrode and electrolyte materials, it will be necessary to optimize component materials for overall device performance.	**ex. Health and Medical Care** Innovation through the integration of cutting-edge semiconductor, electronic, and optical technologies and a vast knowledge in life sciences: DNA and single cells or molecules are detected and identified on artificial nanodevices, such as microfluidic channels. Nanoparticles are employed as transporters in DDS and scaffolding is introduced to immobilize iPS cells and induce the cells to differentiate into desired tissue for innovative diagnoses and medical treatment.
ex. Nanofabrication In addition to device miniaturization and lithography breaking into the sub-10 nm region, there is need for innovation in all component technologies related to fabrication. This development process requires persistent R&D efforts along with the incorporation of new concepts.	**ex. Electronics/IoT** Miniaturization requires thinner gate insulators, but device performance will not be improved with existing SiO_2 layers. High-dielectric materials and new gate electrode materials must be developed. The emergence of technology combining the pursuit of miniaturization with the development of new materials is essential for improving LSI performance.	**ex. Electronics/IoT** There is heightened expectation for integrated systems formed through 3D heterogeneous integration of multiple chips having such diverse functions as storage, logic operations, communication, sensing, imaging, and energy supply, leading to the potential for small robots possessing AI and navigator-like systems that support human lifestyles.

Figure4-2. Three Generations of Nanotechnology and Materials

The third stage is Systems Nano, which is the stage of evolution in which various cutting-edge nanoscale component technologies or new integrated nanotechnologies based on these component technologies are combined. A system of integrated cutting-edge nanotechnologies is precisely what will lead to the IoT/AI age. We define a "nanosystem" as a system that provides, as a whole, sophisticated functions to solve important issues through integration (convergence or fusion) of component technologies and concepts in the field of nanotechnology and materials with those in other fields. Rather than component concepts of nanotechnology, this approach integrates components so that they function as a single system. In the area of nanoelectronics, there is heightened expectation for intelligent chips formed through the 3D heterogeneous integration of various device chips having such functions as storage, logic operations, communication, sensing, imaging, and energy supply. Intelligent chips could be used to develop self-driving systems for automobiles, small robots possessing artificial intelligence, and navigator-like systems that support human activities. In the fields of health and medical care, nanosystems hold potential for spawning great innovation. There are high expectations for innovation brought about through the integration of advanced semiconductor technologies and electronic and optical technologies with the enormous amount of knowledge accumulated in life sciences, as in mounting DNA, cells, or other organism-derived substances on semiconductor chips. In light of this, research has been conducted on innovations in diagnoses, medical treatment, and drug discovery. This includes studies in which organism-derived substances are placed on artificial nanostructures, such as microfluidic channels, to detect and identify DNA, single cells, and single molecules; studies that employ nanoparticles as transporters in drug delivery systems (DDS); and studies in which scaffolding is introduced to immobilize iPS cells and to induce the cells to differentiate into desired tissue.

Fig. 5 shows an example of components for nanotechnology devices that are integrated to form systems in automobiles.

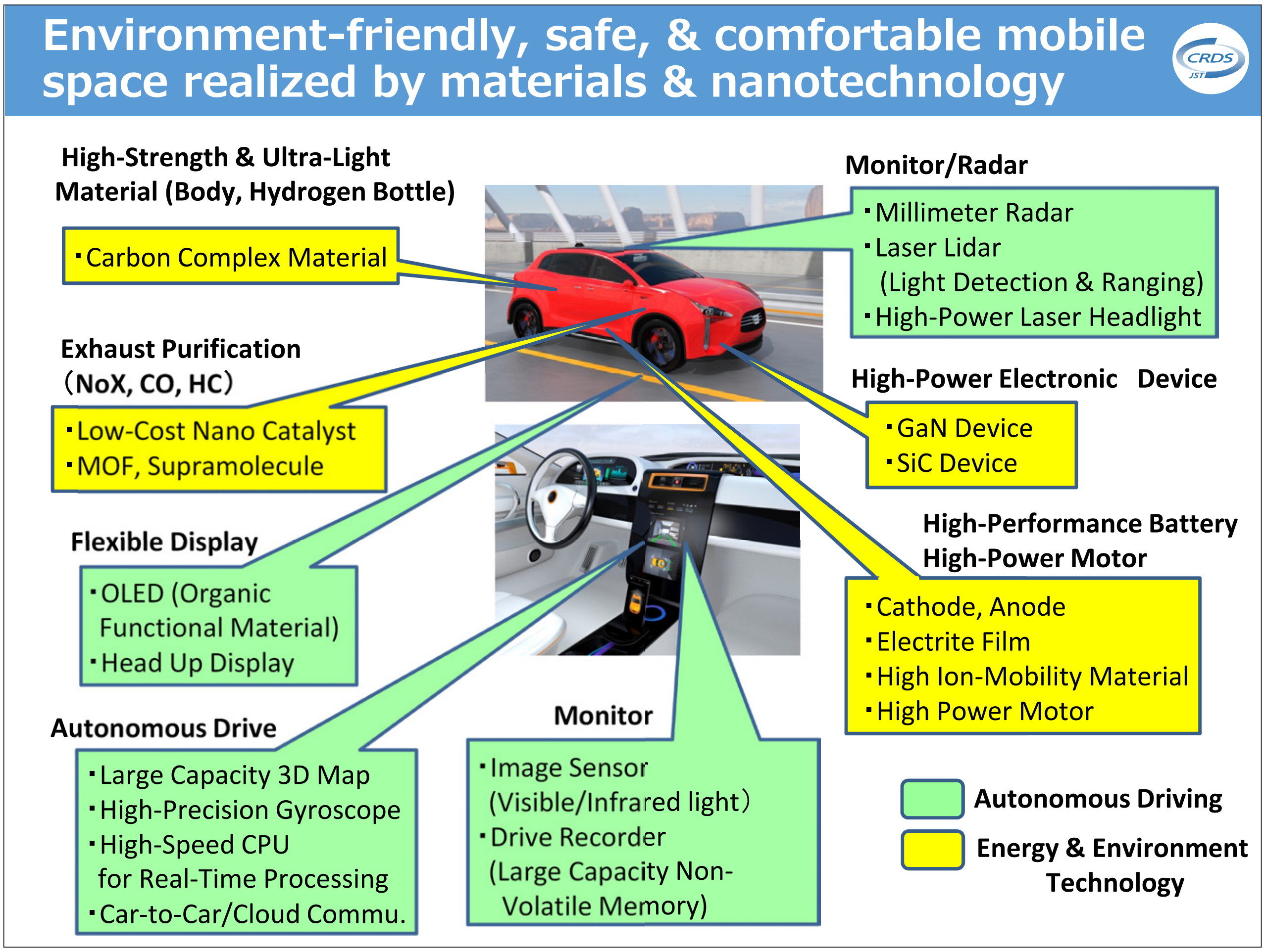


Figure5. Environment-friendly, safe, & comfortable mobile space realized by materials & nanotechnology

3.2 Basic Policies on Nanotechnology Worldwide and Key R&D Programs and Projects in Japan

● Outline and Budgets

This section outlines the principal trends in nanotechnology and materials since 2001 in countries worldwide. Fig. 6 summarizes recent national projects on nanotechnology and materials promoted in major countries around the world.

Basic Policies and Strategies on Nanotech and Materials in Major Countries

Japan		◆ The Fifth Basic Plan identifies integrated material development systems as one of 11 systems that will contribute to Society 5.0, and sets nanotech and materials as a fundamental technology with core strengths for new value creation.
United States		◆ National Nanotechnology Initiative （2001–） -Interagency Nanotechnology Signature Initiatives (NSIs) updated in the 6th NNI Strategic Plan (2016–) -Collaborating with the National Strategic Computing Initiative and BRAIN Initiative to develop computing technologies.
		◆ Materials Genome Initiative (2011–) -To halve the time from discovery to manufacture of new materials in the laboratory through the integration of experimental tools, computers, and data.
Europe	EU	◆ Horizon 2020 （2014-） -Nanotechnology, advanced materials, micro/nanoelectronics, photonics, biotechnology, and advanced manufacturing are selected as key enabling technologies (KETs). -Launched Graphene Flagship as a Future and Emerging Technologie (FETs） project.
	Germany	◆ Action Plan Nanotechnology 2020 (2016-) -Established as a new High-Tech Strategy and coordinated by seven ministries headed by BMBF.
	UK	◆ UK Nanotechnologies Strategy (2010-) -National cross-ministerial nanotechnology strategy headed by the Department for Business, Innovation and Skills (BIS)
		◆ UK COMPOSITES STRATEGY (2009-) -Development led by BIS on light and durable high-performance composites for aircraft and automobiles.
	France	◆ France Europe 2020 (2013-) -Establishes advanced materials, nanoelectronics, nanomaterials, and micro/nanofluidics as priority areas.
China		◆ National Medium- and Long-Term Program for Science and Technology Development (2006-2020) -Sets advanced materials as one of 8 frontier technologies and nanometer studies as one of 4 major sci. programs. -The 13th Five-Year Plan establishes 15 major technology programs envisioned for 2030 that include new materials, quantum communication and computation, smart manufacturing and robotics, and aircraft engines and gas turbines.
South Korea		◆ The 4th Science and Technology Basic Plan (2018-2022) ◆ Korea Nanotechnology Initiative （2001-） entered its Fourth Phase （2016-2025） -Developing leading technology in the manufacturing industry and becoming a global leader in the nanotech industry.

Figure 6-1. Basic Policies and Strategies on Nanotech and Materials in Major Countries

Transition of Nanotechnology-Related Policies in Major Countries

	- 2005 Initiation of Nanotech Policies	2006-2010 Integration of Component Technologies	2011- Nanosystems and Social Implementation
U.S.	1st NNI Strategic Plan (2001) - *NNI budget: $465 M/yr; 20 agencies; NNCO allocated budges for 7 PCAs* - *Component/advanced technologies* - *35 univ. in 21 states participated in the Nanoelectronics Research Initiative* - *Strengthened research infrastructure through NNIN; 13 centers and EHS account for 20% of NNI budget*	2nd NNI Strategic Plan (2006) - *$1.4 B/yr; focus on integrated nanotech research; increased nanobio R&D investment* - *In Obama's Green New Deal, the DOE (1) adopted 46 Energy Frontier Research Centers across the U.S. (80% nanotech), (2) est. ARPA-E and started high-risk high-return projects, and (3) est. 8 Energy Innovation Hubs*	6th NNI Strategic Plan (2016) - *Budget: $1.5 B/yr; renewed the multi-agency NSI; began developing new computing with the National Strategic Computing and BRAIN Initiatives* - *Established NNCI as successor to NNIN, $81 M for 5 yrs; 27 agencies participated at 16 centers* MGI (2011) - *Applying data science to halve the time from discovery to application in materials research*
EU	**EU**: FP6 (2001) **EC**: Towards a European Strategy for Nanotechnology (2004) - *Began prioritizing nanotech with a 5-yr budge of €1,429 M* - *(1) Nanotech/nanoscience, (2) multifunctional materials development from the knowledge base, and (3) new manufacturing process/new devices* - *EU Nanotech & Infrastructure Network at 142 sites throughout Europe*	**EU**: FP7 (2007) - *Doubled the budget of FP6, surpassing U.S.* - *IMEC (Belgium) and MINATEC (France) attracting personnel from global industries* - *Established EU NanoSafety Cluster as a large EU community for ELSI/EHS research* **Ger.** : Nano-Initiative action plan (2010) - *Excellence Initiative to strengthen centers* **UK**: Nanotechnologies Strategy (2010) **UK**: COMPOSITES STRATEGY (2009) - *Est. national center for composites (University of Bristol)*	**EU**: Horizon 2020 (2014) - *4 of 6 KETs are nanotech and materials related (nanotech, advanced materials, micro/nano-electronics, photonics); 7-yr budget of €2.9 B* - *Started Graphene Flagship (€1 B/10 yr)* - *Continued NanoSafety Cluster* **Ger.**: Action Plan Nanotechnology 2020(2016) - *A new High-Tech Strategy; collaboration among 7 ministries led by BMBF for innovation of materials* **UK:** National Graphene Institute (2013) - *Nobel Prize awarded for practical graphene*
China, Korea	**China**: 863 Program,973 Program - *New materials set as 1 of 6 fields* - *Studied nanotech and materials, nanostructured materials* - *Est. National Nano S&T Center (2003)* **Korea**: Nanotechnology Development Plan (2001-) - *3 pillars of R&D, education and personnel development, and research infrastructure; est. 5 NSFC centers*	**China**: National Medium-, Long-Term Program for S&T Development (2006-2020) - *New materials set as 1 of 8 frontier fields* - *Nanometer studies set as 1 of 4 major science programs* **Korea**: 2nd Phase of Nanotechnology Development Plan (2006-) - *Aimed at top 3 in world for nanotech and materials; launched. World Premier Material*	**Korea**: 3rd Phase (2011-2015) and 4th Phase (2016-2025) of Nanotechnology Development Plan - *Est. Nano Convergence Foundation (3rd Phase)* - *Developing nanotech with ethical and social responsibility (3rd Phase) and Nano Safety Management Master Plan across 5 ministries, $83 M over 5 years (2012-)* - *Aims to lead tech. development in industry and to become a global leader in nanotech (4th Phase)*
Japan	2nd S&T Basic Plan (2001) - *Nanotech set as 1 of 4 priority promotion areas* - *Nanotechnology Support Project*	3rd S&T Basic Plan (2006) - *Nanotech set as 1 of 4 priority promotion areas* - *Elements strategy: industry-academia-government collaboration* - *Nanotechnology Network*	4th S&T Basic Plan (2011) - *Interdisciplinary fundamental tech, SIP, ImPACT* 5th S&T Basic Plan (2016) - *Having core strengths for new value creation* - *Elements strategy: est. research center for; Nanotechnology Platform Japan*

Figure 6-2. Transition of Nanotechnology-Related Policies in Major Countries

In 2001 the United States, Japan, and South Korea all launched independent national programs on nanotechnology, followed by Taiwan, China, the European Union, and various other countries. The U.S. in particular treats nanotechnology as an engine for innovation. Beginning from 2006, other nations in Asia, BRICS (Brazil, Russia, India, China, and South Africa) and many other emerging nations established similar national programs on nanotechnology and began investing in cutting-edge science and technology with an eye to innovation. Thereafter, Malaysia, Vietnam, Thailand, and Iran also established national projects in nanotechnology. There now appear to be dozens of nations invested in nanotechnology programs. However, it has become difficult to extract and compare the R&D investments made by each country as each nation employs a different basic structure and method of data aggregation in its policies on science and technology and industrialization.

According to Lux Research Inc., the U.S. is the world's largest investor in nanotechnology R&D from the public and private sectors. While investments by U.S. corporations are on the rise, those by private investors have shown some decline. The level of government investment for nanotechnology in the U.S. declined slightly from approximately US$1.7 billion in 2014, but was holding steady at around US$1.5 billion in 2016. Currently the U.S. leads the world in nanotechnology R&D funding. Second is Japan at US$1.5 billion (2014). However, since Japan broadly appropriates its science and technology budget for fields in nanotechnology and materials, it is necessary to bear in mind that these conditions differ from those in other countries. The E.U.'s total public spending on nanotechnology, when combining all its member states, rose to approximately US$2.5 billion in 2014 and continued to increase another 9.8% over the next two years. Further, products commercialized by nanotechnology (nano-enabled products) expanded rapidly from US$850 billion to US$1.6 trillion during the two years between 2012 and 2014.

The following 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.

● Japan's Science and Technology Policies for Nanotechnology and Materials

■ Basic Policies

After 2000, major countries worldwide established large-scale national investment strategies concerning nanotechnology, but Japan had already been promoting national projects 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 and more than ten other projects promoted by the JST under the Science and Technology Agency as the JST Strategic Basic Research Program ERATO and the Atom Technology Project (for the ultimate manipulation of atoms and molecules), a large-scale project launched in 1992 by the New Energy and Industrial Technology Development Organization (NEDO) under METI. These projects started prior to the construction of the First Basic Plan for Science and Technology (1996) with which Japan 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 National Nanotechnology Initiative (NNI) in the United States. In the Second and Third Science and Technology Basic Plans (2001–5 and 2006–10, respectively), four fields were selected fields to be promoted and another four as priority fields to be promoted. Of the four priority fields to be promoted, nanotechnology and materials was chosen along with life sciences, information and communications, and the environment and had priority in resource allocation over this ten-year period.

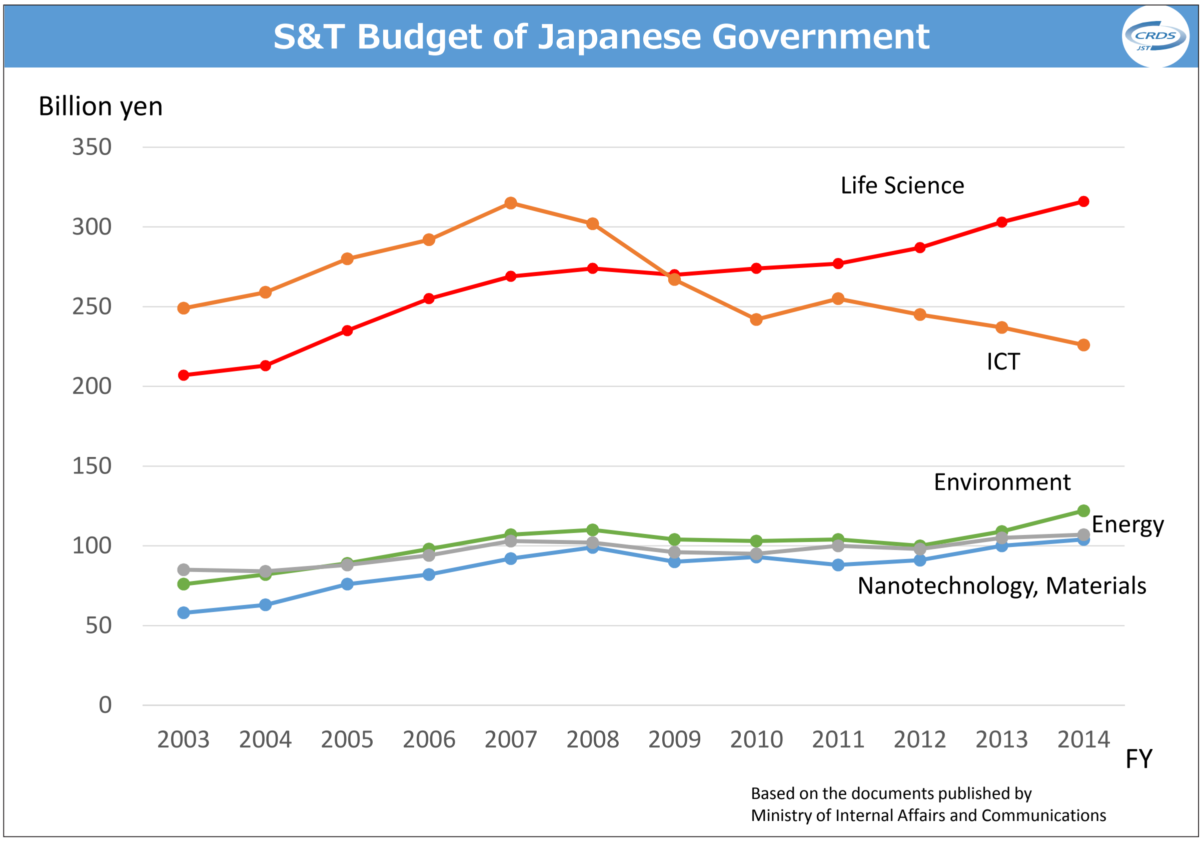


Figure 7. S&T Budget of Japanese Government

In the Third Basic Plan (2006–10), five areas (nanoelectronics; nanobiotechnology and biomaterials; materials; fundamentals promoting the field of nanotechnology and materials; nanoscience and materials science) were identified and promoted as important R&D-related issues in the field of nanotechnology and materials. The following major initiatives and accomplishments were made.[1]

— Upgrading R&D infrastructures such as the X-ray free-electron laser (nationally designated as a critical technology) and the Nanotechnology Network
— Innovation Arena (TIA), 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)

This demonstrates that Japan's continuous and steadfast investment in nanotechnology and materials has begun to produce results in various areas.

In the Fourth Basic Plan (2001–15), policies shifted from promoting prioritized S&T fields to a problem-solving approach in order to meet social expectations (top-down policies). Within this framework, nanotechnologies and materials serve as an interdisciplinary area that intersects the three major policy issues. However, since this interdisciplinary area was not established as an independent initiative, there was a period when some foreign countries perceived that Japan was not placing an emphasis on nanotechnology in its basic policy. Yet, it is clearly stated in the Comprehensive Strategy on Science, Technology and Innovation of 2014 that nanotechnology plays an important role as an interdisciplinary technology that can be used to increase industrial competitiveness and solve policy issues. Nanotechnology is once again clearly established as a common fundamental technology in the Comprehensive Strategy of 2015, wherein one of the priority issues is to foster and reinforce human resources and improve common fundamental technologies including sensors, robots, advanced measurements, light and quantum technology, materials, nanotechnology, and biotechnology toward the realization of a super smart society.

The Fifth Basic Plan (2016–20) notes the achievements and challenges in the basic plans of the previous twenty years, including steady improvements in the R&D environment and such notable accomplishments as receiving the Nobel Prize, as well as a weakening of "basic strengths" in science and technology and a stagnation of government investment in R&D. Against this background, nanotechnology was identified as a fundamental technology possessing core strengths for new value creation. The plan sets aggressive goals from a mid-to-long-term perspective focusing about ten years into the future while considering development toward a super smart society (Society 5.0) and indicates the need to strengthen fundamental technologies toward achieving these goals. Further, by adopting a spiral approach to industry-academia collaboration rather than approaching development according to a linear model that progresses from basic research toward social implementation, there is an emphasis on creating an environment in which new science can be created, innovative technology can be realized, and practical applications and commercialization can be advanced in parallel. The basic plan identifies eleven systems that can contribute to the realization of Society 5.0, one of which is an integrated material development system. The goal is to utilize computational science and data science to create innovative, functional materials and structural materials and to greatly shorten their development time. Of particular interest are cooperative measures established by two ministries (METI and MEXT) and the Cabinet Office on the integrated material development system; materials integration in "Structural Materials for Innovation" (from 2014) of SIP promoted by the Cabinet Office; "Materials Research by Information Integration Initiative (MI^2I)" launched by NIMS as part of JST's support program for starting up innovation hubs under MEXT and "Advanced Materials Informatics through Comprehensive Integration among Theoretical, Experimental, Computational, and Data-Centric Sciences" as part of the JST PRESTO program (both started in 2015), and "Revolutional Material Development by Fusion of Strong Experiments with Theory/Data Science" as part of the JST CREST program (from 2017); and the "Ultra High-Throughput Design and Prototyping Technology for Ultra Advanced Materials Development Project" led by METI, NEDO, and AIST (from 2016). This unprecedented system of conducting complementary R&D in these projects of two Ministries and the Cabinet Office was constructed by the Working Group on Nanotechnology and Materials under the Council for Science, Technology and Innovation (CSTI).

■ Recent R&D Projects

This section provides an overview on the major R&D programs and projects in Japan for the purpose of illustrating current trends in the country's R&D policies. The projects presented in Figures 8 through 14 are related to the field of nanotechnology and materials. Fields are provided for each of the projects according to the categorization used in this report. (Note that if a project belongs to multiple fields, it is listed under its primary field.)

Looking at the overall process from basic research to outcomes (i.e., practical applications or commercialization), the Council for Science, Technology, and Innovation established under the Cabinet Office implements the R&D projects listed in Figure 8 without being restricted by the boundaries of government agencies and fields. The Strategic Innovation Promotion Project (SIP) was initiated in 2014 with the intent of creating promising future markets for industry in Japan and revitalizing Japan's economy. In the same year, the Impulsing Paradigm Change through Disruptive Technologies Program (ImPACT) was launched to encourage high-risk, high-impact R&D on challenging research issues for bringing about great transformations in society and industry.

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

* Related to Nanotechnology and Materials

Strategic Innovation Promotion Program (SIP) (FY2014-)	
Environment/ Energy	Innovative Combustion Technology
	Next-Generation Power-electronics
Social Infrastructure	Technology for Maintenance, renewal and management
	Innovative Structural Materials
Common Fundamental Technologies	Innovative Technology for Design and Production

Impulsing Paradigm Change through Disruptive Technologies Program (ImPACT) (FY2014-)	
Life Sciences/ Health Care	Ultra high-speed multiplexed sensing system beyond evolution for detection of extremely small amounts of substances
	Artificial Cell Reactor Technology for an Enriched and Secure Society and New Bioengineering
Social Infrastructure	Reduction and Resource Recycle of High Level Radioactive Wastes with Nuclear Transmutation
ICT/Electronics	Achieving ultimate Green IT Devices with long usage times without charging
	Advanced Information Society Infrastructure Linking Quantum Artificial Brains in Quantum Network
Common Fundamental Technologies	Super High-Function Structural Proteins to Transform the Basic Materials Industry
	Realizing an Ultra-Thin and Flexible Tough Polymer
	Ubiquitous Power Laser for Achieving a Safe, Secure and Longevity Society
	Innovative visualization technology to lead to creation of a new growth industry

Figure 8. Large Scale R&D Projects of Japan (CSTI)

MEXT maintains research centers from the standpoints of promoting world-class research and industry-academia collaboration and creating innovation (Figure 9). The Creation of Innovation Centers for Advanced Interdisciplinary Research Areas Program has been implemented since 2006 with the objective of supporting the formation of centers that produce results in advanced interdisciplinary research areas having an enormous social and economic impact. The World Premier International Research Center Initiative (WPI) was launched in 2007 with the aim of building world's top-level research centers. Even after the WPI program concluded in 2016 at iCeMS of Kyoto University, MANA of NIMS, and AIMR of Tohoku University, each of these centers has continued conducting their own activities. The Center of Innovation Program (COI STREAM) was started in 2013 for identifying future needs of society to determine a desirable vision for society and our way of life, to break down the barriers of traditional research fields and existing organizations, and to promote industry-academia collaboration on radical innovation that could not be implemented solely in a corporate environment.

Nanotechnology-Related Research Center Project of Japan (MEXT)

* Related to Nanotechnology and Materials

	Center of Innovation (COI STREAM) Program (FY2013-)
Life Sciences/ Health Care	Center of Innovation for creation of a health-conscious society to realize healthy and fulfilling life, and strengthen family ties through unobtrusive sensing and daily health screening
	Center of Open Innovation Network for Smart Health (COINS)
	Self-Managing Healthy Society
	COI Site to develop a "Super Nippon-jin" by activating human power
Social Infra-structure	Construction of next-generation infrastructure using innovative materials
	Global Aqua Innovation Center for Improving Living Standards and Water-sustainability
ICT/ Electronics	The Last 5X innovation R&D Center for a Smart, Happy, and Resilient Society
	Happiness Co-Creation Society through "ISHIN-DENSHIN" Intelligent Communications
Common Fundamental Technologies	Center for Co-Evolutional Social Systems
	Innovative Center for Coherent Photon Technology (ICCPT)

	World Premier International Research Center (WPI) Initiative (FY2007-)
Environment/ Energy	International Institute for Carbon-Neutral Energy Research(I^2CNER), Kyushu University
Life Sciences/ Health Care	Institute for Integrated Cell-Material Sciences (iCeMS), Kyoto University
	Institute of Transformative Bio-Molecules(ITbM), Nogoya University
	Nano Life Science Institute(NanoLSI), Kanazawa University
Common Fundamental Technologies	International Center for Materials Nanoarchitectonics (MANA), NIMS
	Advanced Institute for Materials Research (AIMR), Tohoku University

	Creation of Innovation Centers for Advanced Interdisciplinary Research Areas Program (FY2006-)
ICT/ Electronics	Photonics Advanced Research Center (PARC), Osaka University
	R&D Center of Excellence for Integrated Microsystems, Tohoku University
	Vertically Integrated Center for Technologies of Optical Routing toward Ideal Energy Savings (VICTORIES), AIST

Figure 9. Nanotechnology-Related Research Center Project of Japan (MEXT)

MEXT and METI promote theme-specific programs with various goals, such as the creation of research centers and networks, industry-academia collaboration, and industrialization, which are deemed to deserve government support (Figure 10). Of particular interest among these projects is the Program for Strengthening Innovative Materials Development (M^3) initiated in 2017 with NIMS, which has been promoted to a designated national research and development institute, serving as its core institute.

Major National R&D Projects on Nanotechnology and Materials @FY2017

* Related to Nanotechnology and Materials

MEXT

- Elements Strategy Project (Establishment of Research Hubs)
- Materials Data and Integrated System Project
- Nanotechnology Platform
- M^3 (M-cube) Program
- Program for research and development of next-generation semiconductor to realize energy-saving society
- Photon and Quantum Basic Research Coordinated Development Program
- Photon Frontier Network

METI・NEDO

- Ultra High-Throughput Design and Prototyping Technology for Ultra Advanced Materials Development Project
- The development of production process for high performance lignocellulosic nanofibers and their applications
- Innovative Structural Materials Project
- Innovative Hydrogen Energy Storage and Transport Technology Development
- Project to Develop Cross-sectoral Technologies for IoT Promotion
- Research and development on core technologies for next-generation AI and robots
- Development of Technologies for New Innovative Structural Materials aimed at drastically reducing the weight of transport machines
- Project to Develop Energy-Efficient Chemical Manufacturing Processes

Figure 10. Major National R&D Projects on Nanotechnology and Materials @FY2017

Strategic Basic Research Programs are JST programs employing a top-down approach to competitive funding intended to promote basic research aimed at finding solutions for key issues facing Japan and to produce new and creative technologies that spawn innovation in science and technology. Among these, the CREST program promotes team-based research for creating technological seeds that lead to scientific and technological innovation, while the PRESTO program promotes individual-based research for promising young researchers. In the ERATO program, researchers are guided by brilliant leaders in conducting problem-solving oriented basic research possessing high potential for creating a source of new technologies. Each of these programs provides a framework that enables highly proficient researchers with great potential to freely devote themselves to challenging research subjects believed to be worth pursuing.

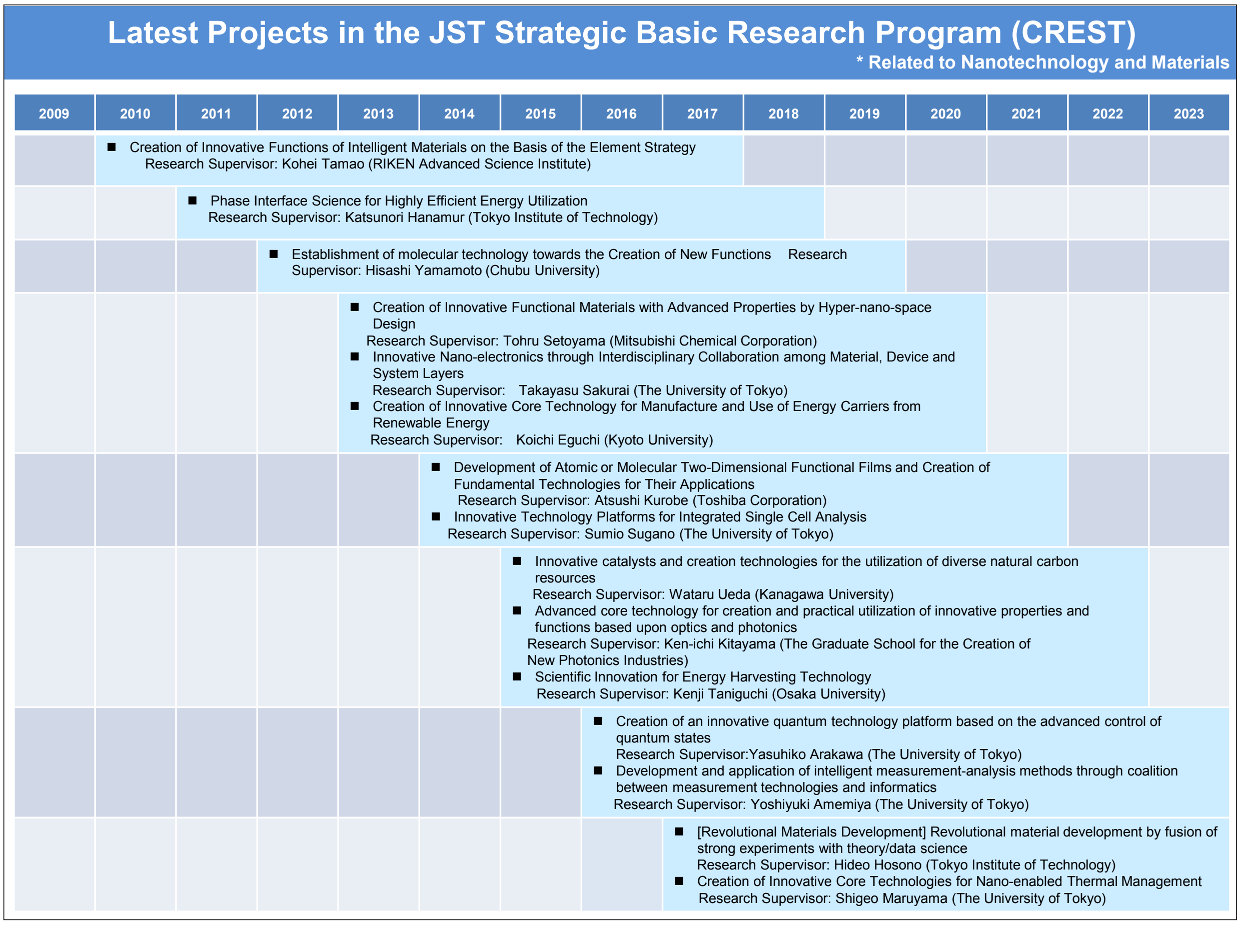


Figure 11. Latest Projects in the JST Strategic Basic Research Program (CREST)

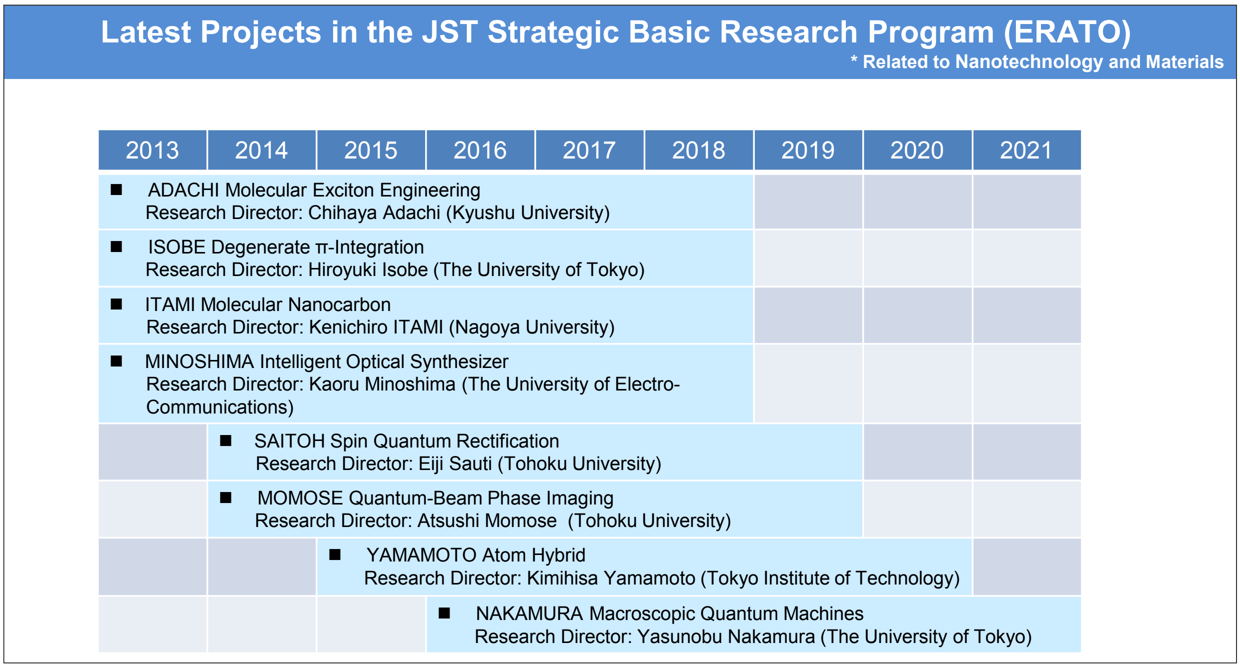


Figure 12. Latest Projects in the JST Strategic Basic Research Program (ERATO)

Besides the Strategic Basic Research Programs, JST promotes unique industry-academia collaborative programs aimed at innovation. The S-Innovation program adopts R&D themes based primarily on the research output from JST's basic research programs and promotes seamless, long-term pursuit of R&D on these topics aimed at finding practical applications for technologies with the potential to form a foundation for new industry. Collaborative Research Programs based on Industrial Demand promote basic research carried out by universities and other institutions that will contribute to solutions for technical issues shared across the industrial sector (technical themes). ALCA promotes R&D based on new scientific and technological knowledge for the purposes of creating technologies that have significant potential to contribute to the reduction of greenhouse gases. ACCEL promotes the management of innovation-oriented research from demonstrating and presenting proof-of-concept to establishing appropriate intellectual property rights. The JST MIRAI Program is a new program initiated in 2017 for conducting R&D toward the pursuit of technically challenging goals, with an eye on targets (research output) that could have an economic and social impact. In addition, some of the above industry-academia collaborative programs have been merged and reorganized (Figure 13, 14).

JST MIRAI Program

Area	Themes of Small Start type (FY2017)
Realization of a Super Smart Society (Society 5.0)	Building a service platform for creation of new services by collaboration and cooperation of various components
Realization of a Sustainable Society	Innovation in manufacturing for new process of sustainable resource recycle
	Improving intellectual capability to enhance "a Socially Active Life" for overcoming the reducing labor force
Realization of the most Safe and Secure Society in the world	Development of the crisis navigator for individuals
	Creation of "humane service" industries
"Realization of a Low Carbon Society, a global issue"	Realization of a low carbon society through game changing technologies

Themes of Large Scale type (FY2017)
Laser-plasma acceleration technologies leading to innovative downsizing and high energy of particle accelerators
High-temperature superconducting wire joint technologies leading to innovative reduction of energy loss
Quantum inertial sensor technologies leading to innovative high precision and downsizing of self-localization units

Figure 13. JST MIRAI Program

Recent JST Projects * Related to Nanotechnology and Materials

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

Collaborative Research Based on Industrial Demand
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
Next Generation Batteries

Advanced Catalytic Transformation program for Carbon utilization (ACT-C)

Accelerated Innovation Research Initiative Turning Top Science and Ideas into High-Impact Values (ACCEL)
Development of high-resolution LIDAR system based on slow-light structures
Creation of the Functional Materials on the Basis of the Inter-Element-Fusion Strategy and Their Innovative Applications
Realization and development of innovative information processing system and application using near-field coupling integration technology
Reinforcement of Resiliency of Concentrated Polymer Brushes and Its Tribological Applications - Development of Novel “Soft and Resilient Tribology (SRT)” System
Development of Key Chemical Processes of Extremely High Efficiency with Super-Performance Heterogeneous Catalysts
Fundamentals and Applications of Diamond Electrodes
Development of Flexible Nitride Semiconductor Devices with PSD
Three-Dimensional Integrated Circuits Technology Based on Vertical BC-MOSFETs and Its Advanced Application Exploration
The Nanospace Science of PCP for Molecular Control
“Photonic Crystal Surface-Emitting Semiconductor Laser” - Towards Realization of High Power and High Brightness Operation
Innovative Molecular Structure Analysis based on Self-Assembly Technology
Materials Science and Application of Electrides

Figure 14. Recent JST Projects

By observing the above programs and projects promoted by Japan, the following keywords emerge as priority areas for R&D investment: 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 substitutes for critical metals and elements. Some of these areas are briefly reviewed below.

● Data-Driven Material Development (Materials Informatics)

In July of 2015, JST selected Materials Research by Information Integration Initiative (MI2I) based at NIMS as the subject of the support program for starting up an innovation hub at a national research institute. In October of the same year, the research project Advanced Materials Informatics through Comprehensive Integration among Theoretical, Experimental, Computational and Data-Centric Sciences was begun as part of the JST Strategic Basic Research Program PRESTO. In the first project, NIMS is constructing a data platform to be used as an open-innovation hub for conducting research on new materials and will develop and make available tools of computational science and data science. The institute has also formed a consortium primarily for users in industry. Members participating in the consortium's activities will be able to use data and tools to develop research techniques through information integration and provide feedback for accelerating this development. The second project promotes independent research by young or mid-career researchers, with studies currently being conducted on various topics related to theory, computation, and experimentation in the fields of solid state physics, chemistry, and materials, as well as information science and mathematical science.

These projects are carrying out complementary R&D to materials integration, one of the R&D topics in the Structural Materials for Innovation program of SIP (2014–18), and to the Ultra High-Throughput Design and Prototyping Technology for Ultra Advanced Materials Development Project promoted by METI and led by AIST (2016–21). Personnel engaged in the research participate in coordination meetings held by the three agencies under METI, MEXT, and the Cabinet Office in order to share their progress and achievements for each project.

- Batteries

In addition to competition in developing high-performance lithium-ion batteries, research is also being conducted toward producing innovative next-generation batteries. The goal is to build a system of fundamental technologies that will enable us to design and manufacture novel batteries with an extremely high energy density not attainable by existing batteries.

Under NEDO's RISING Project, research hubs were established at Kyoto University and AIST for the purpose of developing innovative batteries from basic research to practical application, is underway through industry-government-academia collaboration. This initiative promotes a collaborative system that enables Japanese organizations to conduct basic research and to pursue innovative next-generation batteries through shared use of large-scale, cutting-edge research facilities, such as SPring-8 and J-PARC. Also, under JST's ALCA-SPRING project, a joint research center was set up at the National Institute for Materials Science (NIMS), and large-scale systematic R&D was begun in FY2013. In this project, participating researchers from universities and national institutions in Japan were formed into four groups, each with a primary objective. The scale of these efforts surpasses that of similar efforts in other countries, since most of Japan's researchers specializing in batteries are taking part in these R&D projects.

- Power Electronics

The power semiconductor devices that are currently in wide use are mainly based on silicon (Si), and their performance is improved through advances in microfabrication technology, improvement in wafer quality, the introduction of new manufacturing processes such as low-temperature processing, and improvements in device structure (super-junction MOSFETs and 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 achievable in principle. In the process of realizing practical application of such power semiconductor devices, R&D 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 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. Under JST's Super Cluster Program, research on SiC and GaN crystals and devices is pursued through inter-regional collaboration, with the areas of Kyoto and Aichi serving as core clusters. This research project will continue through March 2018. Research on GaN devices has also been accelerated by the establishment of a crystal growth center (Nagoya University) for the MEXT program entitled "Research and development of next-generation semiconductors to realize an energy-saving society," and establishment of a GaN Advanced Device Open Innovation Laboratory by Nagoya University and AIST.

A large-scale project related to power semiconductor devices under the Cabinet Office's FIRST Program entitled "Innovative SiC Power Electronics Technology toward a 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-academia 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

The following projects related to metallic materials are being carried out: 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; a project in the JST Advanced Low-Carbon Technology R&D Program 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.

After a preparatory phase that began in 2014, the Research Center for Structural Materials was established as a formal organization at NIMS in 2016. The Center works with steel and nonferrous metals, ceramics, and carbon-fiber-reinforced polymers (CFRP), as well as bonding techniques for these materials, such as welding and adhesives. Further, the Center is also developing techniques of long-term damage assessment and nanoscale structural and dynamic analysis for materials. In a project funded by a basic operating expenses grant, the Center is currently engaged in a seven-year plan on basic research related to the relationship on characterization and macro-properties of grain boundaries and heterophase interfaces. METI has promoted the following programs on CFRP: a 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 the implementation of a technology for monitoring the health of aircraft-grade CFRP structures and the development of technologies for monitoring manufacturing processes. 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.

There are two projects that deal comprehensively with structural materials. The first is METI's Research Program for Pioneering the Future entitled "Development of Technologies for New Innovative Structural Materials" (since 2013). This program 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. Participating members include 37 companies, a university, and a national research institute (as of the end of 2016). The goals of the Association are to develop steel sheets having a strength of 1.5 GPa and an elongation of 20% and to design alloys and develop process technologies capable of producing high-performance, low-cost nonferrous metals. Development of CFRP is primarily focused on carbon-fiber-reinforced thermoplastics (CFRTP) employing thermoplastic resin for mass-production of ultra-lightweight automobiles. Under joining technologies, the Association has been engaged in development on various types of welding, including friction stir welding (FSW), and has begun work on adhesion technologies.

The second project is called "Structural materials for innovation," which is part of the Cross-ministerial Strategic Innovation Promotion Program (SIP) initiated in 2014. The goal of this project is to develop strong heat-resistant materials with high specific tensile strength and their process technologies in order to improve the efficiency of aircraft and energy equipment (particularly the former). A total of 78 organizations (as of the end of 2016) participate in the project, including 31 companies, 37 universities, and 10 national and public research institutes. The project has been configured of four R&D domains that have the following subjects of development. Domain A (Polymers and FRP): Development of CFRTP for fans and fan cases used in aircraft engines, non-autoclave CFRP molding technologies, tough composite materials with high-productivity, etc. Domain B (Heat-resistant alloys and intermetallic compounds): Development of forging, casting, powder metallurgy, and design of Ti alloys, Ni-based alloys, and TiAl alloys for use in aircraft engine components (compressors, turbine disks, turbine blades, etc.). Domain C (Ceramic coatings): Development of a ceramic environmental barrier coating (EBC) for protecting ceramic matrix composites (CMC) anticipated to be the next generation of turbine blade materials, etc. Domain D (Materials integration (MI)): Development of a materials integration system that greatly reduces the time required to develop materials by integrally applying numerical simulations, theoretical and practical knowledge, experiments, databases, and data science to determine processes, structures, properties, and performance.

● The Elements Strategy

The strategic initiative "Elements Strategy" issued by JST's CRDS in October of 2007 led to MEXT and METI launching the first cross-ministerial projects that same year, entitled the Elements Strategy Project (MEXT) and the Project for Developing Substitutive Materials for Rare Metals (METI). In 2010 MEXT established the strategic objective "Creation of innovative functions of materials by application of nanoscale material structural control technologies, such as controlling the atomic arrangement, toward the practical use of rare-metal-free materials and new targeted functions, such as ultra-high coercivity and ultra-high fracture toughness." To achieve this strategic objective, JST established a research area under the strategic basic research program CREST, entitled "Creation of Innovation Functions of Intelligent Materials on the Basis of Element Strategy" and a new research area under PRESTO entitled "New Materials Science and Element Strategy". In 2012, MEXT started the Elements Strategy Project for Creating Research Centers as a ten-year project. A governing board was established for this project and the related project by METI and NEDO so that the ministries could coordinate their R&D efforts. As some of the more remarkable outcomes from this research, in July of 2016 Daido Steel and Honda Motor Co., Ltd. succeeded in jointly developing a neodymium magnet without the use of heavy rare-earth elements. The magnets were already being used in hybrid vehicles released that same year. Also, in November of 2016 Toshiba Corp. and Toshiba Materials successfully developed a high-iron concentration samarium-cobalt magnet that is free of heavy rare earth elements and announced jointly that they would begin shipping samples of the magnets. Further, the EU, the United States, and Japan have been holding the Trilateral Conference on Critical Materials since 2011 to continue a discussion on technologies for the substitution or reduced use of rare metals and recycling technologies.

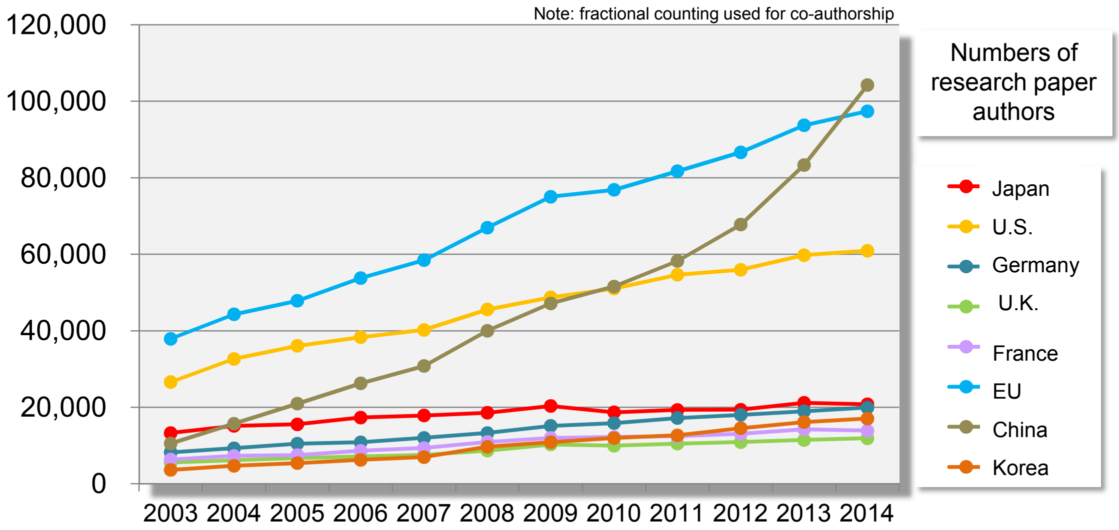
● Artificial Photosynthesis and CO_2 Utilization

In the NEDO project entitled "Development of Process Technologies for Production of Basic Chemicals Using Carbon Dioxide" (2014–2021), Professor Domen of the University of Tokyo together with companies participating in the Japan Technological Research Association of Artificial Photosynthesis Chemical Process (ARPChem) are studying photocatalysts having a high energy conversion efficiency that produce hydrogen using solar energy for water splitting, with the aim of developing a practical and innovative chemical manufacturing process that does not rely on fossil resources but imitates part of the photosynthesis process in plants for producing basic chemicals, such as plastic raw materials from CO_2 and hydrogen obtained from sunlight and water. In an interim report for the project issued in 2016, the organization reported that a solar energy conversion efficiency exceeding 3% was achieved in hydrogen production, with the ultimate goal being a conversion efficiency of at least 10%. The project also succeeded in Z-scheme water splitting using particulate photocatalyst sheets. By simply coating the sheets with particular hydrogen evolution and oxygen evolution photocatalysts, the sheets split water without the need for an external circuit in this scheme.

3.3 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 25,000 as of 2014, which ranks the country third after China and the United States (Figure 15). However, while the numbers of researchers contributing papers in the field of nanotechnology and materials worldwide have increased nearly twofold in both Europe and the United States, nearly sixfold in China and nearly 3.3 times in South Korea since 2005, the number of researchers in Japan has grown only about 1.3 times. 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.

Trends in the Research Community (Research Papers)



Trends in the number of researchers based on papers authored

- The number of researchers authoring papers in nanotechnology and materials increased worldwide.
- The number of researchers authoring papers in Japan is approximately 20,000, which ranks third behind China and the U.S.
- However, while the numbers of contributing researchers have increased nearly 2x in Europe and the U.S., 10x in China, and 5x in South Korea, the number in Japan has grown only about 1.5x.

Figure 15. Trends in the Research Community (Research Papers) in the field of nanotechnology and materials

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 is remarkable for China and South Korea. According to the 2016 edition of Indicators of Science and Technology issued annually by MEXT, the countries having the largest numbers of researchers in order from largest to smallest are the United States (1,253,000 in 2011), China (1,524,000 in 2014), Japan (867,000 in 2015), Russia (445,000 in 2014), Germany (360,000 in 2014), South Korea (345,000 in 2014), and the United Kingdom (274,000 in 2014). The proportion of corporate researchers among the total in each country is highest in order from the United States (81.6% in 1999), South Korea (78.7% in 2013), Japan (74.1% in 2015), China (62.1% in 2014), and France (60.4% in 2014). The proportion is lower in major European countries, including the United Kingdom (38.2% in 2014) and Germany (56.8% in 2014).

The following data was generated by JST based on Scopus Custom Data from Elsevier. Looking at the general trend of research papers in this field, China's position has grown considerably over the last ten years or so. The country ranks first in the world in terms of quantity (number of papers) and, as of 2014, was nearly even with top-ranked EU for the top 10% most cited papers. Japan continues to show little change in terms of both quality and quantity of research papers.

(1) When considering the total number of papers published worldwide using a fractional count for co-authorship (Figure 16), China was first in 2014, followed by the EU, the United States, and Japan. 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.

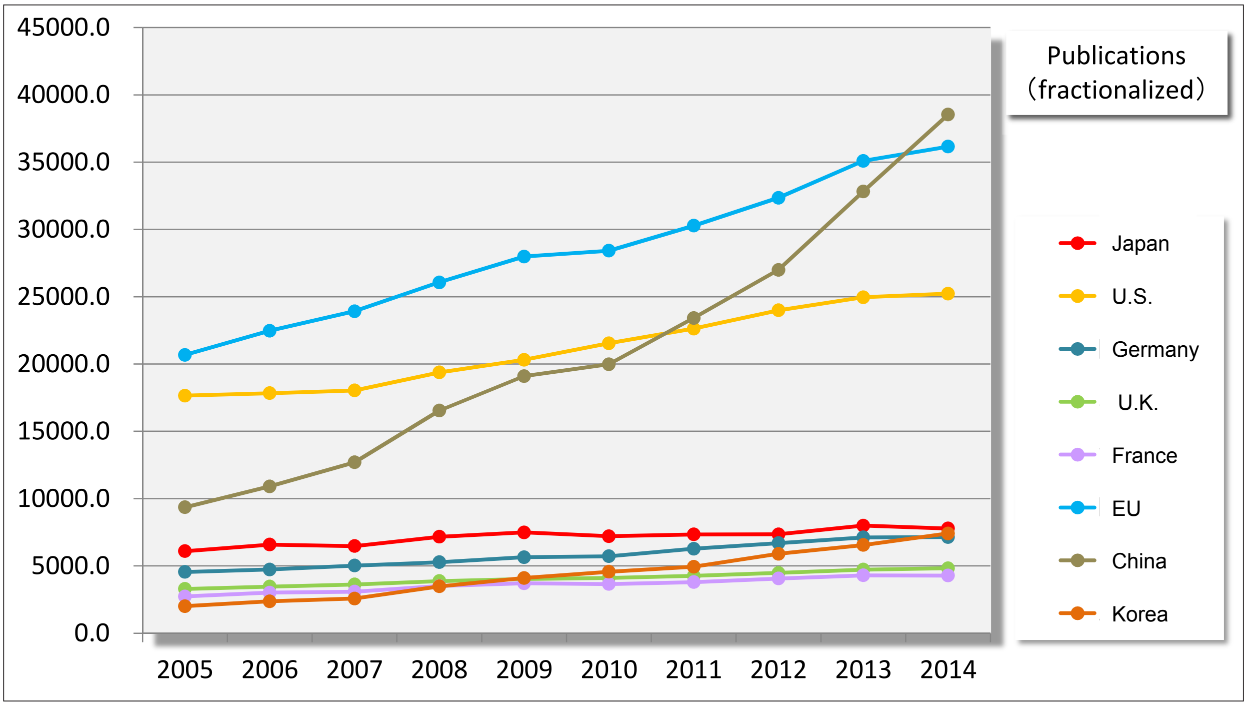


Figure 16. Total number of papers published worldwide in the field of nanotechnology and materials

(2) In terms of the number of papers among the top 10% most cited based on a fractional count (Figure 17), in 2014 the EU and China were roughly even at the top, followed in order by the United States and Germany. Here again, the robust increase in numbers for China is distinctive. Japan occupied the third place in 2005, following the EU, but has presently fallen behind China, the United States, Germany, and South Korea.

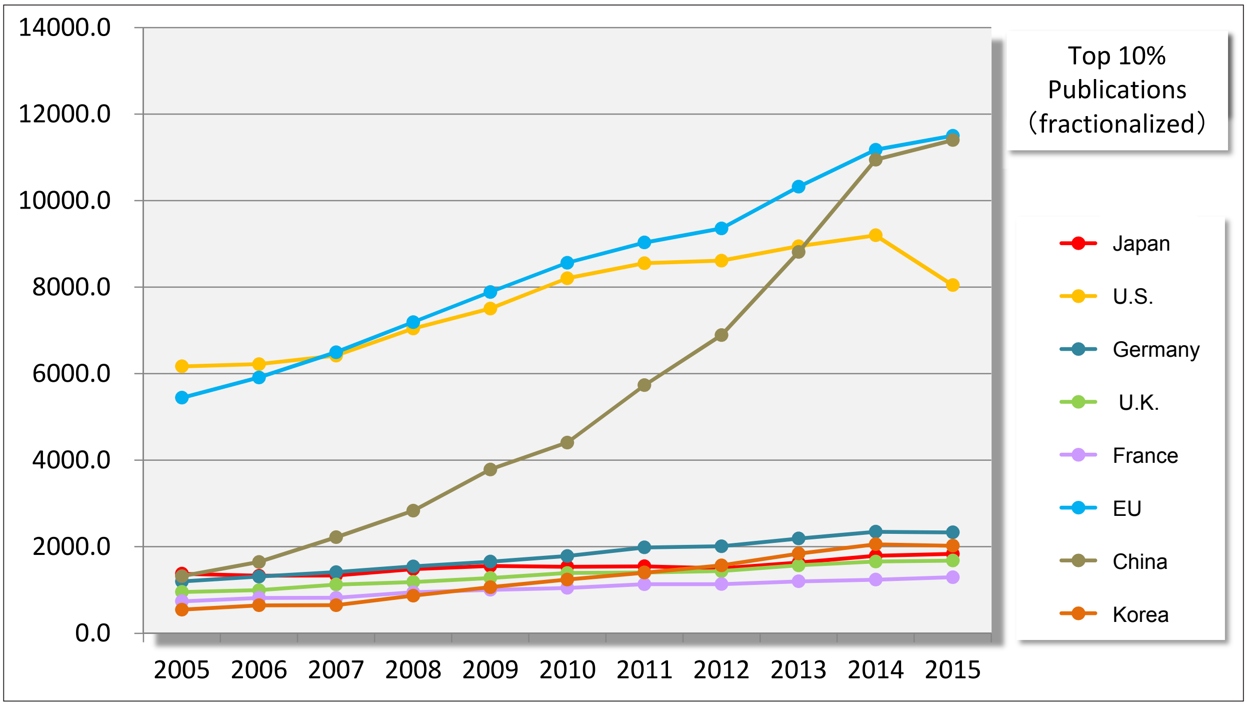


Figure 17. The number of papers among the top 10% most cited in the field of nanotechnology and materials

3.4 Global Trends in R&D

(1) Trends in Major R&D Areas

The following section describes major R&D trends in six areas corresponding to the panoramic view of R&D on nanotechnology and materials.

• 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, green catalysts, and separation materials and engineering. This is because they are closely related to the use of renewable energy, efficient storage and conversion of energy, reduction in CO2 emissions, and water purification. In many of the aforementioned areas, research activities are increasing worldwide. Research on battery devices and power semiconductors in particular is intensifying in many countries.

Japan has increased its commitment to covering the entire process from basic research to commercialization in all the afore-mentioned R&D areas and to enhance its national projects on artificial photosynthesis, thermoelectric conversion, battery devices, and power semiconductor devices in particular. However, a slight decline in activity in the solar cell and green catalyst industries suggests that Japan will need to intensify R&D in these areas.

● Nanotechnology and Materials Related to Life Sciences and Health Care

From basic research to the commercialization phase, research activity in bioimaging is on an upward trend. Multiple large-scale research projects on measurements for brain and neural activity have been initiated worldwide. The increased activity in this field may be attributable to advances in bioimaging-related technologies.

The level of basic research in this area continues to be high in Japan. However, Japan's strength in basic research has not translated directly to a high level of competitiveness in commercialization for most areas, excluding bioimaging. Japan continues to fall behind in the field of biomaterials, in particular. Common factors in the low level of commercialization are the lack of major companies entering the market and an environment that does not adequately support startup companies.

● Nanotechnology and Materials Related to ICT and Electronics

In nanoelectronics, the R&D of semiconductor circuits and devices has shown increased activity worldwide, particularly in the AI computing chips and nonvolatile memory devices such as ReRAMs and MRAMs. Increased activities are being observed also for device applications with new two-dimensional atomic layer materials including graphene. They are expected to play an important role in the coming AI and IoT age. Trials for AI chips to be applied in the autonomous driving and robotics have already started.

Although Japan has traditionally shown its strength in the areas of spintronics and organic electronics, there has been no conspicuous changes in the fields of photonics and nanoelectronics. Further, while Europe and the United States were first to initiate R&D on two-dimensional functional atomic layers, Japan hopes to catch up through JST's CREST and PRESTO projects initiated in 2014. Japan has produced several achievements in topological insulators, which have attracted a lot of attention as a new material, and anticipates more progress in the future.

● Nanotechnology and Materials Related to Social Infrastructure

The Research and Development Project for Innovative Structural Materials was initiated in Japan in 2013 with the goals of developing various materials including composites, and establishing joining technologies for these materials. Along with the development of multi-materials, it is necessary to elucidate the mechanisms of joining dissimilar materials and strength development and to establish experimental methods for closely mapping microscopic structures at the interface to local bond strengths. At the same time, it will be necessary to learn the strength and fracture behavior at junctions of dissimilar materials and to establish multiscale simulating techniques based on this understanding. Materials informatics that applies theoretical and numerical models and data science is being used as powerful techniques for the property prediction and structural design of new materials.

A couple of new technologies related to structural materials are becoming popular, which are high-entropy alloys and additive manufacturing. High-entropy alloys are multi-component alloys having a solid solution of multiple elements. The texture of the high-entropy alloys is controlled by adeptly applying atomic size ratios and chemical potential differences. Researchers are actively pursuing the development of materials with good balance between tensile strength and fracture resistance (ductility) and the elucidation of their mechanisms. Before now, additive manufacturing was typically used to control the external shapes of objects, but as the precision of additive manufacturing improved, the target gradually shifted to structural control for which metallic materials are well suited. Carbon fibers are principal elements in composite materials, and are expected to be used in many applications of structural materials. Japan continues to maintain its overwhelming edge in the global market for production of carbon fibers, but competes with other countries in joining technologies.

- Nanotechnology and Materials Related to Functional Design and Control

Functional design and control of nanotechnology and materials are both the fundamental and ultimate goals of this field. In recent years, and particularly since the U.S. announcement of the Materials Genome Initiative in 2011, data-driven materials development has been actively promoted worldwide. Owing to Japan's enhanced funding system through such projects as the Grants-in-Aid for Scientific Research on Innovative Areas by the Japan Society for the Promotion of Science (JSPS) and the JST Strategic Basic Research Program, Japan has aggressively engaged in the basic research phase. In the applied research and development phase, JST and NIMS are leading the active pursuit of research in this area through the MI^2I program.

- Common Fundamental Science and Technology for Nanotechnology and Materials

The common fundamental technologies in this field include manufacturing and processing, measurements and analysis, and theoretical and computational science. For manufacturing and processing, microfabrication technologies developed in the area of semiconductor devices are not confined to the semiconductor field, but have spread to nanomechanics, photonics, and bionanotechnology. Advances in extreme ultraviolet (EUV) exposure systems have been utilized to develop a technology for producing devices with single nanometer dimensions in order to overcome the limits of device miniaturization. Other promising areas include nanoimprint lithography, self-assembly of nanostructures, and maskless lithography such as direct-write electron beam lithography. The number of leading semiconductor manufacturers who can develop advanced semiconductor LSI chips has reduced dramatically throughout the world partly due to the necessity of huge investment for the technologies, placing Japan's technological development on advanced microfabrication in a difficult spot. The Evolving Nano-Process Infrastructure Development Center (EIDEC) is a private consortium in Japan that conducts R&D on next-generation devices and the improvement and control of nano-level defects in the device.

One global trend in the area of measurement and analysis is the progress in operando measurements, which are technologies for observing changes over time in physical parameters of various devices under operating conditions. The importance of such measurements has particularly increased in such industrial and technical fields as batteries, catalysts, and tribology. Japan has seen rapid advances in operando measurement technologies through scanning probe microscopy (SPM), transmission electron microscopy (TEM), and synchrotron radiation. Operando measurements using synchrotron radiation are expected to have continued uses and applications in the development of lithium-ion batteries and fuel cells. Spectroscopy using high-energy X-rays (Compton scattering, etc.), X-ray computed tomography, and coherent diffraction imaging is also expected to rapidly improve our ability to visualize nanostructures of devices directly.

Theoretical and computational science supports the foundation of materials science, applying our accumulated knowledge in quantum mechanics and statistical mechanics to establish technologies for high-precision analysis and prediction of material structures, properties, textures, and chemical reaction mechanisms. Research activity on simulation and modeling technologies has been particularly brisk in recent years owing to remarkable progress in computer performance and software developments.

Notable Trends

CRDS has identified the following research topics as recent trends in global R&D (Figure 18).

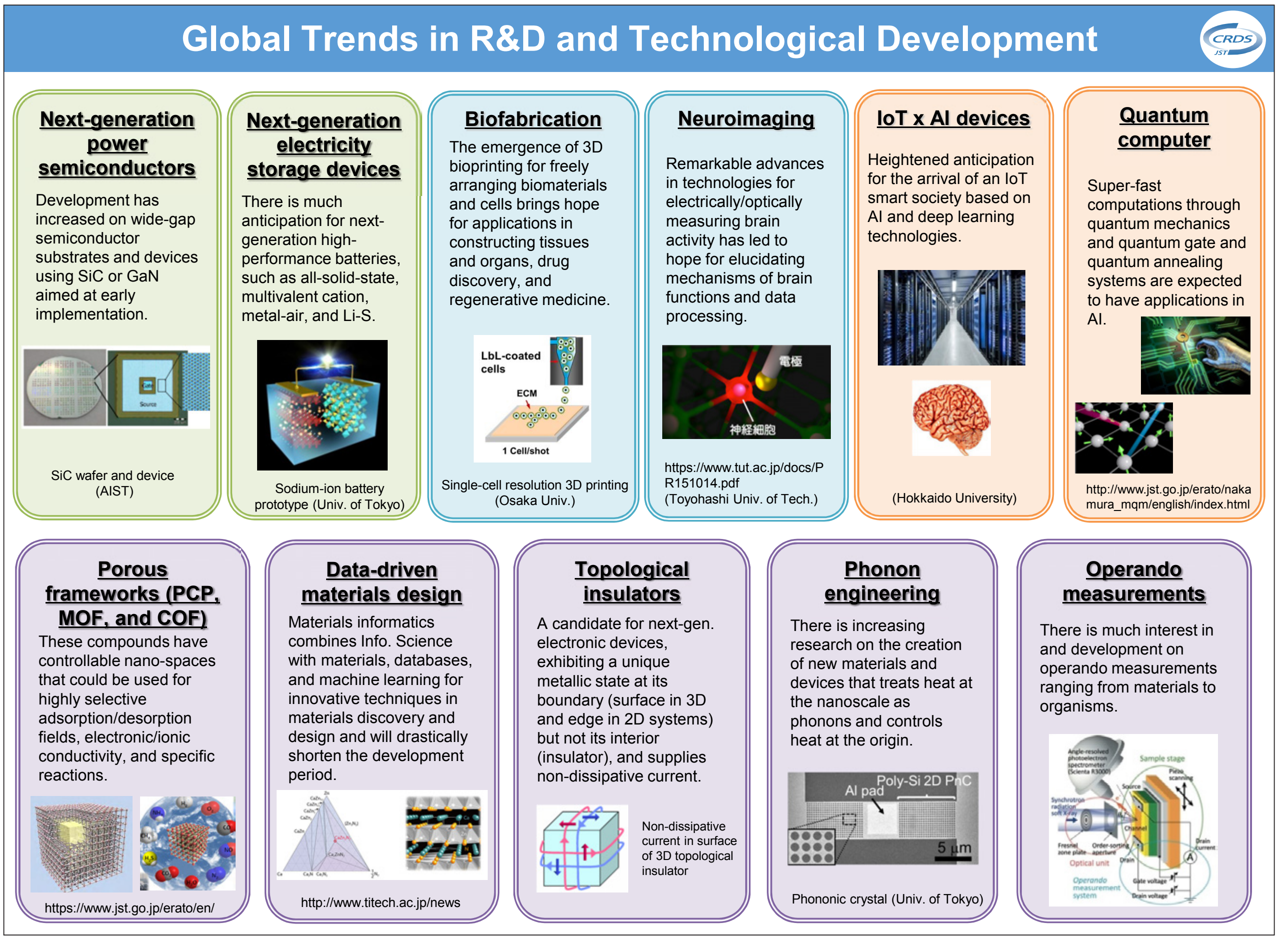


Figure 18. Global Trends in R&D and Technological Development

• <u>Next-Generation Power Semiconductors</u>

It has become a pressing need worldwide to find solutions to such environmental problems as global warming, abnormal weather, and desertification by fundamentally re-examining our inefficient mass consumption of energy and promoting a change from traditional fossil fuel energies to renewable energies in order to reduce carbon dioxide emissions. However, the ratio of electric power consumption to total energy consumption continues to increase every year, leading to heightened expectations for the use of power-saving technologies in a vast range of power equipment related to the transport, conversion, control, and supply of electric power. For this reason, the development and spread of power semiconductors for use in high-efficiency rectifiers and switches will be essential, and such power semiconductor devices must be developed with higher breakdown voltage and lower loss (lower on-resistance).

The most common power semiconductors today are silicon-based, but it has been shown that the material properties of silicon limit 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 achievable in principle.

SiC is currently being used to develop various commercial power devices, with several manufacturers from Japan, the United States, and Europe having entered the market. Energy-efficient inverters are already being incorporated in air conditioners and are now beginning to be used as inverters for railway trains. Research is also being conducted on in-vehicle devices. However, these devices are not yet sufficiently advanced in terms of performance and reliability and will need to undergo extensive R&D from substrate materials and processes to devices, circuits, and modules. Such R&D is actively being pursued by Japan, the United States, and Europe in particular.

Further, although there are still many issues with GaN substrates, power semiconductor devices based on this material are expected to realize high-speed operations, resulting in the small-sized power modules. For this reason, there has been much activity in R&D on GaN-on-Si substrates and freestanding GaN substrates, as well as lateral HEMT structures and vertical devices. Research on gallium oxide (Ga_2O_3) and diamond, which have a larger band gap than SiC and GaN, is also becoming active.

● Next-Generation Electrical Energy Storage Devices

Electrical energy storage devices are not limited to portable consumer applications, as the market for these devices is rapidly expanding into electric vehicle applications. This expansion is accompanied by higher performance requirements for reliability, durability, and power output characteristics, and competition in technological development in this field has heated up around the world. In our efforts to maximize use of renewable energy, the requirements of stationary electrical storage devices with a large energy capacity have begun to emerge based on the objective of absorbing and smoothing voltage variation to produce constant output, particularly for load-leveling and peak-shifting in the demand side.

Against this background, there has been an upsurge in research on various batteries regarded as next-generation systems capable of surpassing the performance of present-day lithium-ion batteries, including all-solid-state batteries that are deemed to be safe against combustion, and metal-air batteries and lithium-sulfur batteries that have high-energy density. Research on redox flow batteries has also been popular, particularly overseas.

Research on all-solid-state batteries is expected to lead to the development of solid electrolytes possessing ionic conductivity comparable to liquid electrolytes as a means of resolving issues of deformation, expansion, and combustion caused by overheating. Solid electrolyte materials are generally classified as oxide-based, sulfide-based, or polymer-based. Recently, the Tokyo Institute of Technology and Toyota Motor Corporation discovered $Li_{10}GeP_2S_{12}$ (lithium, geranium, phosphorus, and sulfur (LGPS)), a sulfide-based solid electrolyte exhibiting ionic conductivity nearly equivalent to that of organic electrolytes.

There has been worldwide interest in research on lithium-air batteries using oxygen in the air as the cathode because the properties of air electrodes have improved greatly since 2012 when ether-based electrolytes were employed. Research has not been confined to academia either, as many of the world's leading automobile manufacturers, including Toyota, Honda, Hyundai, and BMW, are conducting their own studies. As for lithium-sulfur batteries, sulfur is being considered as a cathode for post lithium-ion batteries, because they have an extremely high specific capacity of 1,675 $mAhg^{-1}$, although the discharge potential of sulfur is lower than that of layered oxides used in the present Li-ion batteries, approximately 2V relative to lithium. Research is also being carried out on inorganic solid electrolytes and polymer electrolytes due to the fact that sulfur intermediates tend to dissolve in the presence of organic electrolytes.

One major type of redox flow battery uses an aqueous sulfuric acid solution containing vanadium ions as the electrolyte. In the battery cell, a diaphragm is interposed between the cathode and anode. A cathode electrolyte and an anode electrolyte are supplied to the battery cell from respective external tanks to effect charging and discharging. These rechargeable batteries store energy in the solutions contained in these external tanks. Sumitomo Electric is one of the leading developers of redox flow batteries in Japan. Some of the advantages of redox flow batteries is that they have an extremely long cycle life of 10,000 times or greater, they can produce instantaneous power output several times the design value for short intervals, and are capable of instantaneous response on the order of milliseconds. They are also highly safe and exhibit little degradation under normal temperature operations. On the other hand, they have low energy density, require a pump to circulate the electrolytes, and are necessarily bulky in size. The number of research papers on these batteries has increased considerably overseas in the last several years. The United States, in particular, has launched several R&D projects since 2009, and the results of this research have begun to emerge in recent years.

• Biofabrication

Biofabrication is a technology for constructing primarily tissues and organs possessing biofunctions in vitro. A large focus of this research is the application of biological processes so far, such as biomineralization. In addition to advances in cellular research of recent years, developments in micro/nano-fabrication and micro/nano-fluid device technologies have enabled us to construct tissues and organs possessing 3D structures and functions that approach actual biological tissue. These results have attracted attention for their potential applications in the regenerative medicine. In particular, the emergence of 3D printing technology capable of arranging cells and biomaterials in desired positions (bioprinting) has led to a surge in the numbers of researchers in the field worldwide, as well as the establishment in 2010 of the International Society for Biofabrication.

In 2016 the Advanced Tissue Biofabrication Manufacturing Innovation Institute (ATB-MII) was established under the U.S. network, Manufacturing USA (formerly the National Network for Manufacturing Innovation), for the purpose of promoting the development of commercial products and industries related to tissues and organs produced through biofabrication. In Japan, research was conducted for the Grant-in-Aid for Scientific Research on Innovative Areas "Hyper Bio Assembler" (2011–2015) aimed at creating a methodology for constructing 3D cellular systems that function in vitro. An AMED project started in 2014 entitled "Development of the functional biotissue production technology by the three-dimensional shaping" has carried out research on the development of technologies for fabricating biological tissues and organs with a 3D printer. While there are many technical challenges in fabricating large tissues and organs, such as the need to construct a network of capillary blood vessels, biofabrication shows great promise for its application in research on drug discovery and regenerative medicine, as well as its potential for constructing tissues and organs suitable for transplantation therapy.

● Monitoring Brain Activity

Research on monitoring brain and neuron activity has become very popular in recent years, with the launch of large-scale research projects around the world. The BRAIN (Brain Research through Advancing Innovative Neurotechnologies) Initiative started in 2013 in the United States has set goals for imaging the entire brain of a fruit fly and the entire hippocampus of a mouse within 10 years, and imaging the entire cerebral cortex of a conscious mouse within 15 years. In Europe, the Human Brain Project started in 2013 aims to develop compact, low-power data processors by integrating information communication technology with neuroimaging, establishing an ICT-based infrastructure, and developing neuromorphic engineering for modeling the brain's structure and functions, and robotics. Brain/MINDS is a project launched in 2014 in Japan to elucidate the entire neural network responsible for brain functions using innovative technologies. This project uses primarily MRI-based imaging to map the brain structure and functions of a marmoset, a small primate, with the aim of developing translational biomarkers through human brain mapping corresponding to the nonhuman primate brain and clinical research, and to develop innovative technology that contributes to brain mapping.

Japan has maintained a high level of research on imaging-related technologies and has supported research on brain imaging through the development of new fluorescent probes and technologies to make a biological tissue transparent, as well as superior fundamental technologies on optical microscopes and MRI. A future challenge will be processing the large quantity of data that is expected to grow enormously with advances in whole-brain imaging and analysis. Establishing a data processing technology will require a multidisciplinary approach toward integrating information and computer sciences, and an acceleration of cross-ministerial collaboration, establishment of a funding system, and development of human resources. Another issue to address is the standardization of data analysis methods.

• IoT and AI Devices

Nanotechnology forms the foundation to produce devices with higher speed, smaller size and lower power consumption and has made artificial intelligence (AI), deep learning, accelerators for intelligent data processing, and brain-type computing a reality. The arrival of a genuine IoT age in which these nanotechnology-derived devices can be linked together over a vast sensor network is approaching.

With the progress of deep learning and the emergence of enormous quantities of big data, AI is opening up new possibilities and making great strides toward practical applications. It is also believed that the day will soon come when we actually begin relying on AI-based automated driving and personal assistants. The progress made in AI research is largely due to the introduction of deep learning. Utilization of deep learning has led to tremendous advances in the development of image recognition, natural language processing, and self-learning robots. At the same time, remarkable advances have been made in sensor technology, which is indispensable for the IoT age. In 2013, the Trillion Sensors Movement started in the United States. The project aims at realizing the 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 activities. Big data will be used in a wide range of situations and will significantly change society and people's lives. Although the concepts like the IoT and machine to machine (M2M) seem to be similar to the Trillion Sensor Movement, communications and networks play the central role in the former but the sensor devices have major role in the latter.

• Quantum Computing

In 2015 the joint team of Canada's D-Wave Systems and Google announced that their quantum computer D-Wave 2X with about 1,000 qubits was able to solve a specific optimization problem 100 million times faster than a conventional computer. 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 computing program, is robust against noise, and is faster than the classical simulated annealing process.

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 quantum computation code 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 reading qubits.

In 2015, the Intelligence Advanced Research Projects Activity (IARPA) initiated their projects called QEO (quantum annealing systems) and LogiQ (quantum gate systems) in the United States. In Japan, the "Quantum Information Processing Project" under the Funding Program for World-Leading Innovative R&D on Science and Technology (FIRST) was established to conduct research on superconducting qubits, qubits using electron spin, or hybrid quantum systems thereof, and from 2014 R&D on this theme was continued as the "Advanced Information Society Infrastructure Linking Quantum Artificial Brains in Quantum Network" under the Impacting Paradigm Change through Disruptive Technologies (ImPACT) program. In 2016, as part of JST's Strategic Basic Research Programs, the research area "Creation of an innovative quantum technology platform based on the advanced control of quantum states" under CREST, the research area "Quantum state control and functionalization" under PRESTO, and the project "NAKAMURA Macroscopic Quantum Machines" under ERATO were launched as part of "the cultivation of a new physical property and information science frontier by high-level control of the quantum state," one of the strategic objectives established by MEXT.

• Porous Frameworks (PCP, MOF, and COF)

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). Dr. Omar Yaghi (University of California, Berkeley) and Dr. Susumu Kitagawa (Kyoto University) and colleagues established the concepts of porous coordination polymers (PCP) and metal-organic frameworks (MOF). These are new types of porous materials with infinite skeletal structures created by linking organic ligands through coordinate bonding with metal ions (i.e., obtained from simple compounds through a simple reaction). The concepts 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, began participating 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. Other functionality, including Electrical conductivity, reaction fields, sensors, energy harvesting, and medical applications, has recently attracted attention and continues to expand the range of applications for porous frameworks. R&D on covalent organic frameworks (COF) as a porous molecular crystal similar to MOF has also increased around the world. Unlike MOFs, COFs do not include metal in their skeletal structure, but have a crystalline network structure configured only of organic elements. Since COFs, like MOFs, have good design flexibility, many researchers around the world are engaged in the development of these materials.

Research is ongoing in the area of hyper-nano-space design established under both CREST and PRESTO at JST and in two research topics established at ACCEL based on PCPs entitled "The Nanospace Science of PCP for Molecular Control" and "Innovative Molecular Structure Analysis based on Self-Assembly Technology." Future requirements will include scale expansion, from nano to macro; crystallinity control and strengthening of the structures that prevent an overall collapse, even during integration and expansion; and high-speed, high volume synthesis and cost reductions adapted to a practical time frame and available resources.

• Data-Driven Materials Design

The Materials Genome Initiative (MGI) established in the United States in 2011 sparked a revolution in techniques for material discovery and design by combining the use of technologies in information science, such as materials databases and machine learning, with traditional theoretical, experimental, and computational sciences. Now, techniques for data-driven materials development that can shorten the development period are being actively pursued worldwide. The combinations of materials targeted in materials science are massive in number and are distinctive in that even slight differences in the combination can greatly alter the properties.

In Japan, Center for Materials Research by Information and Integration established at NIMS in 2015 has been conducting research on materials informatics. In addition to developing and improving their materials database, the center at NIMS creates a system of industry-academia-government collaboration over a wide range of areas, from materials science to informational and mathematical sciences. By forming a consortium, the center aims to construct an open innovation hub for encouraging broader involvement among companies. As its mission, the center tackles specific research themes, including battery materials, magnet materials, and thermal conducting materials, aiming at their implementation in society. In addition, the research area "Advanced Materials Informatics through Comprehensive Integration among Theoretical, Experimental, Computational and Data-Centric Sciences" was also established in 2015 under the JST Strategic Basic Research Program PRESTO with the objective of establishing fundamental technologies in materials informatics and producing the next world-class young research leaders to further the field.

• Topological Insulators

Lately there has been a lot of attention paid to topological insulators, materials that do not fall into the typical solid categories of metals, semiconductors, and insulators. A topological insulator behaves as an insulator in its interior, but exhibits a unique metallic state in its boundary (its surface in 3D systems, and its edge in 2D systems). Electrons flowing through this metallic state have almost zero mass and exhibit their spins polarization determined by their flow direction (spin-momentum locking). Unlike in ordinary materials, electrons in the boundary of topological insulators possess robust properties against nonmagnetic defects and impurities. Consequently, there are great expectations for the applications of topological insulators in spintronics and quantum computing.

Topological insulators are often compared to graphene, in particular, since the electronic state in the surface of a three-dimensional topological insulator constitutes a Dirac fermion system. However, topological insulators have many advantages over graphene in the creation of devices, such as their spontaneous formation of two-dimensional thin films, their ease in spin control owing to spin-momentum locking, and their diversity of materials.

Japan accomplished world-leading results in topological insulators and peripheral topological materials in such projects as “Quantum Science on Strong Correlation” (2009–13) under the Cabinet Office’s Funding Program for World-Leading Innovative R&D on Science and Technology (FIRST Program) and “Creation of Innovative Devices based on Topological Insulators” (2010–13) under the Funding Program for Next Generation World-Leading Researchers (NEXT Program), and is steadily building a foundation for fundamental technologies in the projects “Topological Quantum Phenomena in Condensed Matter with Broken Symmetries” (2010–14) and “Topological Materials Science” (2015–2019), both awarded by JSPS Grants-in-Aid for Scientific Research on Innovative Areas.

• Phonon Engineering

Solutions to such issues as the coming information explosion and the need for more efficient energy utilization in the forthcoming society will require innovations in devices used for information processing and for thermoelectric conversion. The understanding and control of thermal properties in nanostructures and on very short time scales will be indispensable for finding these solutions. The issue of heat generation and dissipation in devices miniaturized to the nanoscale in particular is an impediment to improving the performance of semiconductor integrated circuits. Hard disk drives are also facing a major hurdle in expanding their capacity due to the issue of thermal fluctuations in nanoscale magnets. Therefore, there is a strong desire to either resolve these issues by developing nanoscale heat control methods or to develop devices with new operating principles for proactively utilizing heat generation on a nanoscale.

Under such circumstances, it will be vital to understand how heat behaves at the nanoscale and to control and utilize its properties. At the nanoscale, heat transport in a material must be treated in terms of the transport of phonons, which are quanta of lattice vibrations. The concept of phonons was first discovered around the beginning of the 20th Century. However, an understanding of and the control technologies for heat at the nanoscale based on phonons took much longer to develop than those for electronic and optical properties since a deep understanding and control have rarely been necessary for device development to date. On the other hand, as the miniaturization of electronic devices, optical devices, and magnetic devices advances to the nanoscale, a correct understanding and designing of device operations is impossible as long as electrons, photons, spins, and phonons are treated separately. For this reason, it is necessarily to establish a new academic discipline and to work toward the innovation of materials and devices by deepening our understanding of heat in nanoscale regions from the perspective of nanoscience and to establish new technologies of heat control and utilization.

In applied areas of thermoelectric conversion, there has been an increase in research activity on controlling heat conduction by treating heat conduction in a solid (phonon conduction) as particles and increasing phonon scattering through the introduction of impurities, crystalline structures, and structural defects. There has also been a dramatic increase in research on phononic crystals that utilize the wave properties of phonons and, similar to electrons and photons, prevent or slow the transmission of specific phonons through interference or the formation of band structures. Further, fundamental simulation technologies for simulating heat conduction across the range from nanoscale to macroscale in an integrated manner and for simultaneously simulating the transmission of electrons and phonons is making it possible to estimate the characteristics of semiconductor devices with great accuracy. There has also been an increasing amount of development on new devices that heat nanowires or other nanomaterials to be utilized as ultra-low-power gas sensors and high-speed light-emitting devices. As one example, the spin Seebeck effect was discovered in Japan as a new principle of thermoelectric conversion. This discovery is expected to lead to new applied fields since the path of heat conduction is perpendicular to the path of electric current.

In Japan, JST introduced two new research areas in 2017 that include “Creation of Innovative Core Technologies for Nano-enabled Thermal Management” under CREST and “Thermal Science and Control of Spectral Energy Transport” under PRESTO.

• Operando Measurements

For materials to be used in energy and the environment and the area of life sciences, there is an increasing need for measurements in diverse environments, including under water and in the air, along nano-shapes formed in surfaces, at junctions of dissimilar interfaces, and under friction conditions. Above all, there is strong demand for operando measurements used to observe and measure operating conditions or simply the state of existence of a target in situ, including dynamic observations of catalytic reactions, dynamic observations in batteries during charging and discharging, observations of frictional wear in tribology, and dynamic observations in vivo. The word “operando” carries a strong sense of conducting practical measurements under operating conditions and is distinguished from the more conventional “in situ” that simply deals with changes in properties caused by external fields. Research is being conducted overseas with great enthusiasm at many synchrotron radiation facilities. The time is ripe for making significant advances in operando measurements for a wide range of fields, from materials science to life sciences, using scanning probe and electron microscopes, synchrotron/X-rays, neutron beams, and ultrashort pulse lasers.

With regard to operando measurements using SPM, scientists are exploring industrial applications for technologies on measuring electric potential and physical properties primarily focused on measurements of surface potential, charge distribution, and impurity-density distribution. With basic research in the area of atomic force microscopy (AFM) in ultra-high vacuum conditions having progressed to a highly advanced level, studies to expand on this research that are performed in air and in liquid have intensified throughout the world and are being applied to electrode reactions that occur in batteries of various types, chemical reactions in the corrosion of metals, catalytic reactions, and enzyme reactions.

With operando measurements using an electron microscope, it is desirable to measure actual operations under a complete in situ environment. Operando measurements on the operating states of lithium-ion batteries must be performed under complete atmospheric conditions. It is thought that more advances in technological development will be required to create this complete atmospheric environment in order to perform various types of measurements.

The purpose of operando measurements using synchrotron radiation is to visualize changes in the crystalline structures and electronic states of materials in semiconductor devices, batteries, and other devices during operations. X-rays are suitable as a probe for operando measurements in that they do not influence the operating state of the object being measured. Further, since parts responsible for governing functions of a device are rarely exposed on the outside of the device, it is necessary to capture changes in the states of parts inside the device. Here, effective analysis can be performed with X-rays or neutron radiation, both of which have good penetrating ability. Another challenge will be to establish operando X-ray spectroscopic analyses focusing on chemical and magnetic changes in elements characteristically found in the parts being observed.

In operando measurements using ultrashort pulse lasers, it is possible to track the dynamic processes of electrons, atoms, and molecules in active devices. For example, in a catalytic reaction occurring during operations, the reactive species on the surface of the catalyst undergoes a continuous series of processes including adsorption, diffusion, structural change, and desorption. A future challenge will be to develop a measuring technology for monitoring these operating processes with satisfying both nano-order spatial resolution and temporal resolution ranging from nanoseconds to picoseconds.

(2) Main Achievements in Japan (Past Ten Years)

For more than half a century as an advanced country, Japan has been one of perennial leaders in academic research, technological development, and industrial activity that have produced actual products in the field of nanotechnology and materials and has produced much scientific knowledge and technologies. Since the turn of the century, R&D activities in Japan have consistently 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 on nanotechnology and materials.

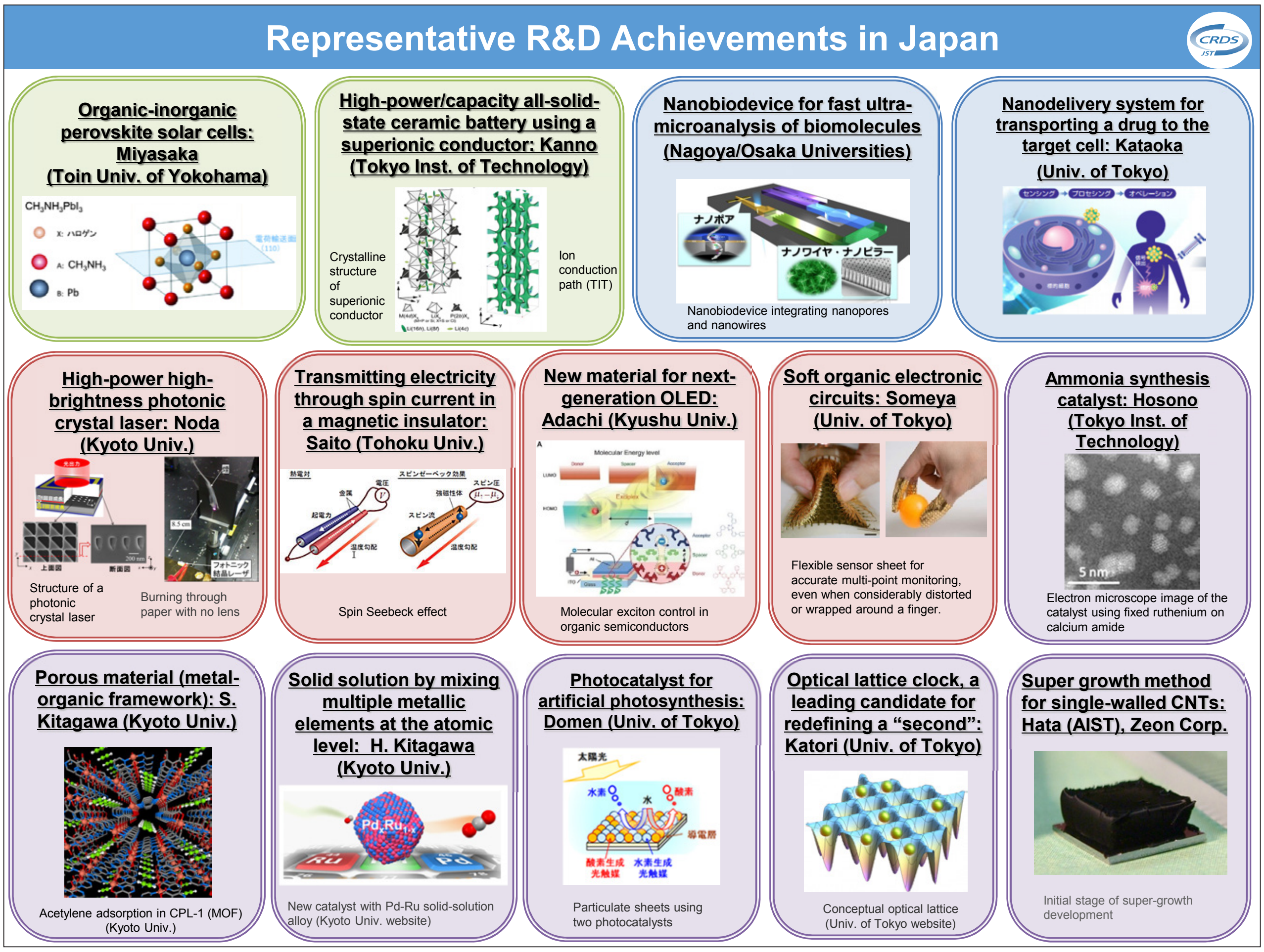


Figure 19. Representative R&D Achievements in Japan

Figure 19 shows sample 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. This figure illustrates just a few of the achievements made in Japan, but there are obviously too many to illustrate here.

(3) A Summary of Five Workshops Held by CRDS

The following section summarizes five workshops held by CRDS on the topics of materials design and control; nanoelectronics; interdisciplinary research merging biotechnology and life sciences with nanotechnology and materials; social infrastructure; and ELSI/EHS for nanotechnology. Many of Japan's leading researchers attended these workshops, which were held for the purposes of compiling notable trends in science and technology, technologies that will be needed in the future, and the future directions of R&D.

1) Workshops on Materials Design and Control

The workshops were conducted from two points of view: new direction of condensed matter physics, and the creation of new materials and functions. The following direction and goals for future research were summarized from the workshop on new direction of condensed matter physics.

- Future direction of R&D
  - Conduct R&D from the perspective of quantum phases and topology that applies new understanding to known materials and that is coordinated with the design of new materials and the development of new devices.
  - Break from traditional condensed matter physics that deals with the near-uniform and near-equilibrium states of electrons to produce spatially nonuniform electronic textures (superstructures) derived from electron interaction and to control these textures using an external field. Also, create and control nonequilibrium states, such as dynamic electron phase transitions and transient responses, using an external field
  - Develop innovative technologies in spectroscopy that optimize temporal and spatial resolutions based on recent developments in spectrometry, time-resolved measurements, and scanning probes.

The following direction and goals were summarized from the workshop on the creation of new materials and functions.

- Future direction of R&D
  - Create game-changing materials that defy conventional wisdom and revolutionize materials science.
  - Pursue the specific properties and potential of water that makes up the Earth, life, and ecosystems and that circulates in environments while transitioning among its

three phases.

- Produce innovation in neuroscience through a materials science based approach to the unique chemicals likely playing a role in the intricate workings of the brain, which are mediated by complex systems and networks.
- Create new chemical concepts through the integration of AI and computational science.
- Create new processes of chemical cycling for principal elements (nitrogen, phosphorus, etc.) indispensable for maintaining development of a sustainable society.
- Elucidate the dynamic mechanical behavior of materials at spatial scales ranging from the molecular level to the macro-scale and create new materials with controlled mechanical behavior.
- Develop technologies that actively apply biological functions and construct and utilize systems not in thermodynamic equilibrium by understanding and controlling spatiotemporal processes in crowding/dissipative material systems, such as phenomena of life, material transport, and interfacial phenomena.

The following policy and organizational related issues were drawn up by both workshops.

- Issues of policy and organization
  - A proper research environment is necessary for ensuring a seamless process from theoretical clarification using theory and computations to materials development, measurements and assessments, and device development.
  - Indices for properly evaluating nonequilibrium systems must be standardized.
  - In order to integrate biological sciences with chemistry and physics, it will be important to create a framework that encourages communication among the different fields.
  - Interdisciplinary human resource development not confined within the framework of chemistry, physics, biology, computational science, and information science will be important.
  - Stimulating global personnel exchange will be necessary for demonstrating Japan's presence in the world.

2) Workshop on Nanoelectronics

The following were identified as important issues for R&D in the area of next-generation nanoelectronics of the post-Moore era.

- Future direction of R&D

When developing new device technologies in the IoT age typified or represented by AI and brain-type computers, it will necessary to apply new hardware technologies actively to AI accelerators designed to execute deep learning and other processes. This will require that the accelerator and high-capacity memory be connected with a wide bandwidth and that dataflow in the accelerator is flexibly reconfigurable. To achieve this, it will be necessary to formulate R&D that wholly integrates materials, devices, circuits, and architectures. The use of this accelerator may be envisioned to be at the edge or fog level rather than in the cloud. Sensor networks also play a leading role in the IoT age. It will be essential to build smart sensor networks that link together numerous devices. Another interesting subject is a brain-type computer with a neuromorphic architecture. The basic research in this area might include research on the artificial creation of nerve cells themselves and research on the artificial creation of synapses for connecting nerve cells to each other. Recent developments in memristors and ReRAM have led to increased R&D activity on neuromorphic devices. However, due to the barrier that exists between device materials and circuit architectures, Japan has focused rather on software research in the developments of AI.

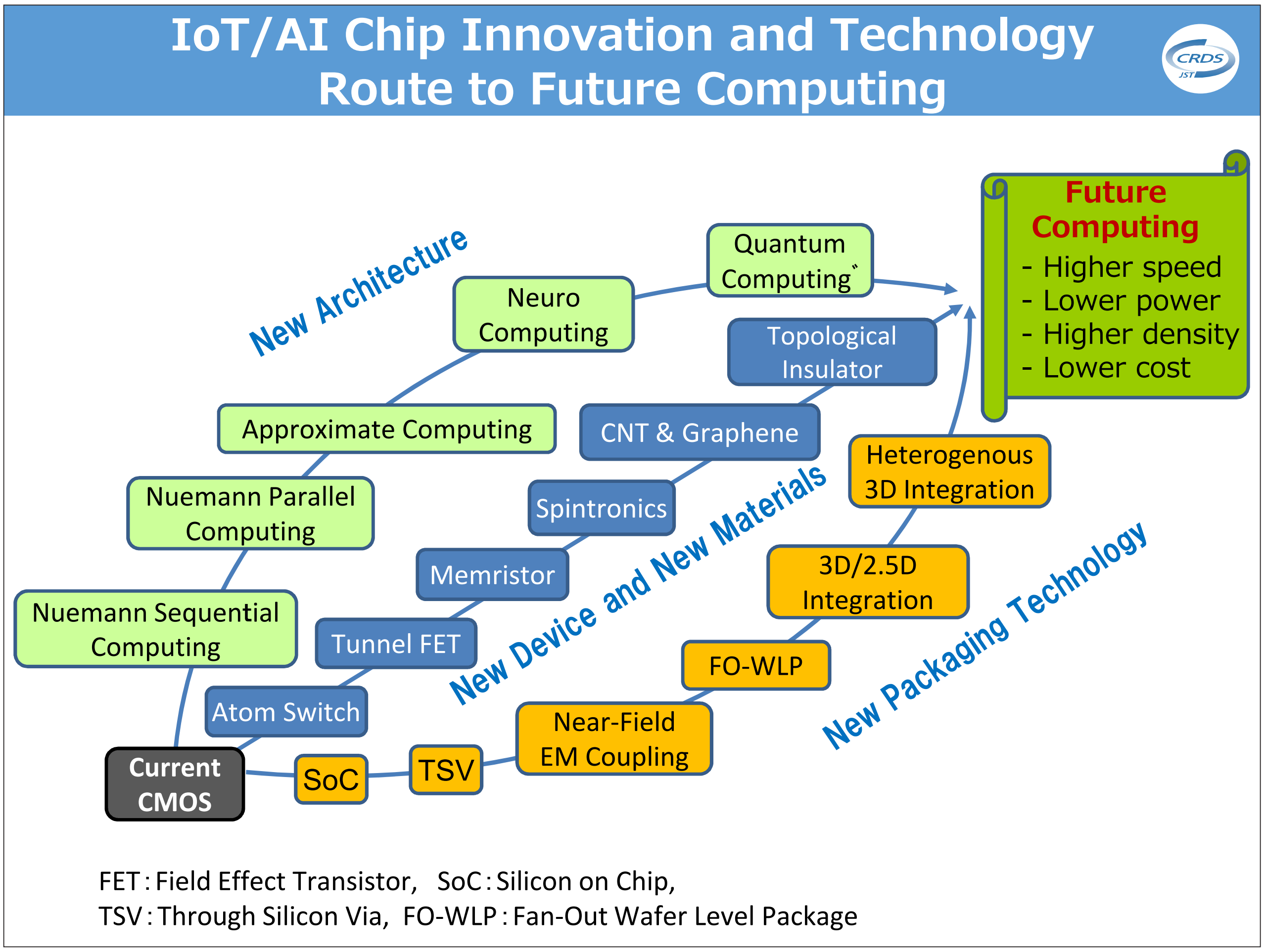


Figure 20. IoT/AI Chip Innovation and Technology Route to Future Computing

In the meantime, we have recently seen remarkable advances in quantum computing, which may serve as the foundation for future computing technologies. A major advantage of quantum computing is its computing capability to solve some specific problems which cannot be solved substantially by the present computers. In terms of applications, its use in machine learning is likely to have the greatest impact in society. It is important to establish a technology for quantum error correction in order to realize a universal quantum computer employing quantum gates. Recent technological advances have made implementation of such error correction technologies more feasible, intensifying competition in research primarily among IT companies. It is important to enhance Japan's presence in the world by producing device circuits and architectures from original ideas. It would be desirable to take part in an international research network on quantum computing so that Japan can have a role in global collaboration. Humankind has only just now obtained the ability to utilize the concept of quantum coherence, and much research must be conducted to learn how it can be applied.

3) Workshop on Areas Merging Biotechnology and Life Sciences with Nanotechnology and Materials

Interdisciplinary areas merging biotechnology and life sciences with nanotechnology and materials are important fields for driving innovation in biotechnology and life sciences and health and medical care on the foundation of nanotechnology and materials. This multidisciplinary field includes research areas that could spark innovation not only in medical fields but also in life science and other fields including molecular robotics, molecular nanosystems, synthetic biology, artificial cells, nano-/micro-robots, and nanomachines (Figure 21).

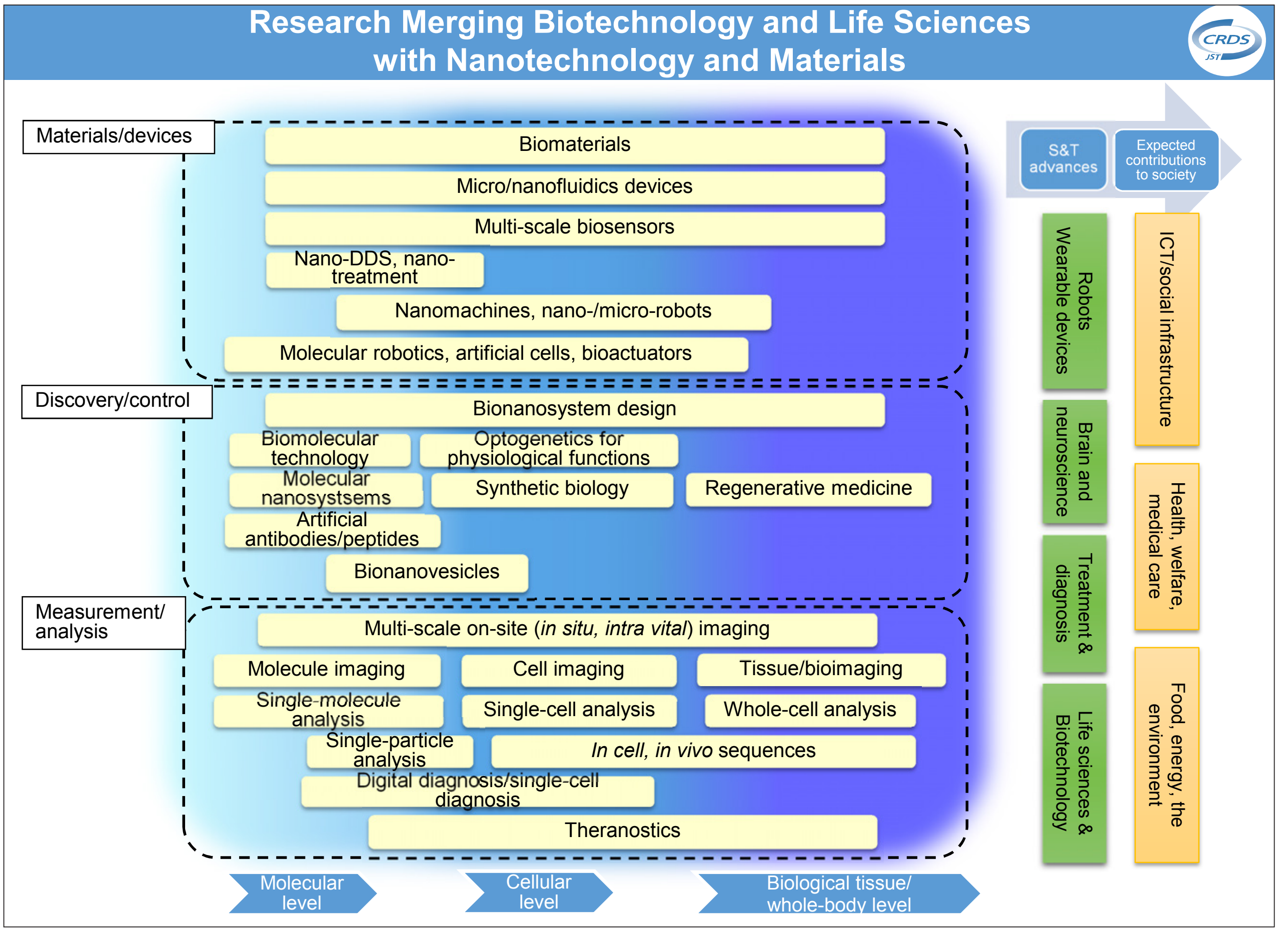


Figure 21. Research Merging Biotechnology and Life Sciences with Nanotechnology and Materials

- The future direction of R&D and technological challenges
  - Much work is being done to develop techniques for single-molecule comprehensive analyses or quantitative analyses on such biomolecules as peptides, proteins, and nucleic acids. In addition to developing pre-processing technologies that will enable us to select a specific cell to be measured and to extract a desired biomolecule from within the cell, it will be particularly important to satisfy both comprehensive and quantitative analyses and to develop in cell and in vivo sequences.
  - While striking advances have been made in bioimaging technologies, we are still not able to measure or analyze living cell dynamics at the single-molecule level. There is a need for a technology to observe protein-protein interaction and protein-biomaterial interaction within cells and to observe cell responses to these interactions on site (in situ/intravital imaging). Multi-scale observation technologies will also be needed to gain a comprehensive understanding of biofunctions.
  - Much research is being carried out on creating three-dimensional biological tissues. However, the problem of tissues dying due to a deficiency of internal nutrients and oxygen has not been resolved. It is necessary to construct a vascular network within

the tissue and to develop a substitute substance for blood.

— In order to utilize the superb functions possessed by cells, such as their sensing capability, a more advanced approach will be needed in which cells are used to fabricate hybrid biomaterials and biodevices.

— A massive amount of data is collected through bioimaging and other technologies. New techniques for processing and analyzing data must be established by integrating information science and technology.

— For biodevice application of materials, problems at the interface with biomolecules should be solved Technologies for controlling the interaction at these interfaces are extremely important.

— Clarifying the interaction between a living organism and biomaterial is required for research at any stage, from the molecular level to the biological tissue/whole-body level, and is also essential for the creation of novel biomaterials and devices.

— For advances of the brain science including elucidation of brain functions and mental functionality perturbation, development of AI-based technologies as well as nanobiosystems will be necessary.

— Molecular robotics, molecular nanosystems, synthetic biology, artificial cells, nano-/micro-robots, and nanomachines are extremely important technologies that may spark innovation, not only in medical fields, but also in life sciences and other fields. It will be important to maintain a library and establish standards for keeping it systematic.

— R&D is needed on systems integrating biomolecular technology with nanotechnology, including optogenetics for physiological functions, genome editing, and the cell wall tectonics.

4) Workshop on Social Infrastructure

Various issues must be studied from a perspective of nanotechnology and materials in order to establish and maintain a robust social infrastructure. These include technologies for systematic maintenance; structure formation technologies, such as structural materials, joining and bonding technologies, and coatings and surface treatments; and technologies for elucidating the mechanisms of deterioration and corrosion; assessing measurements, inspections, and analyses; predicting deterioration and remaining life; and repair work. It will also be necessary to address engineering techniques that handle both old and new structures together, the formation of numerical models for various corrosive environments, technologies for predicting corrosion and the initiation of fatigue cracks in welded parts, methods of compiling histories and maintaining databases on materials, and recycling perspectives.

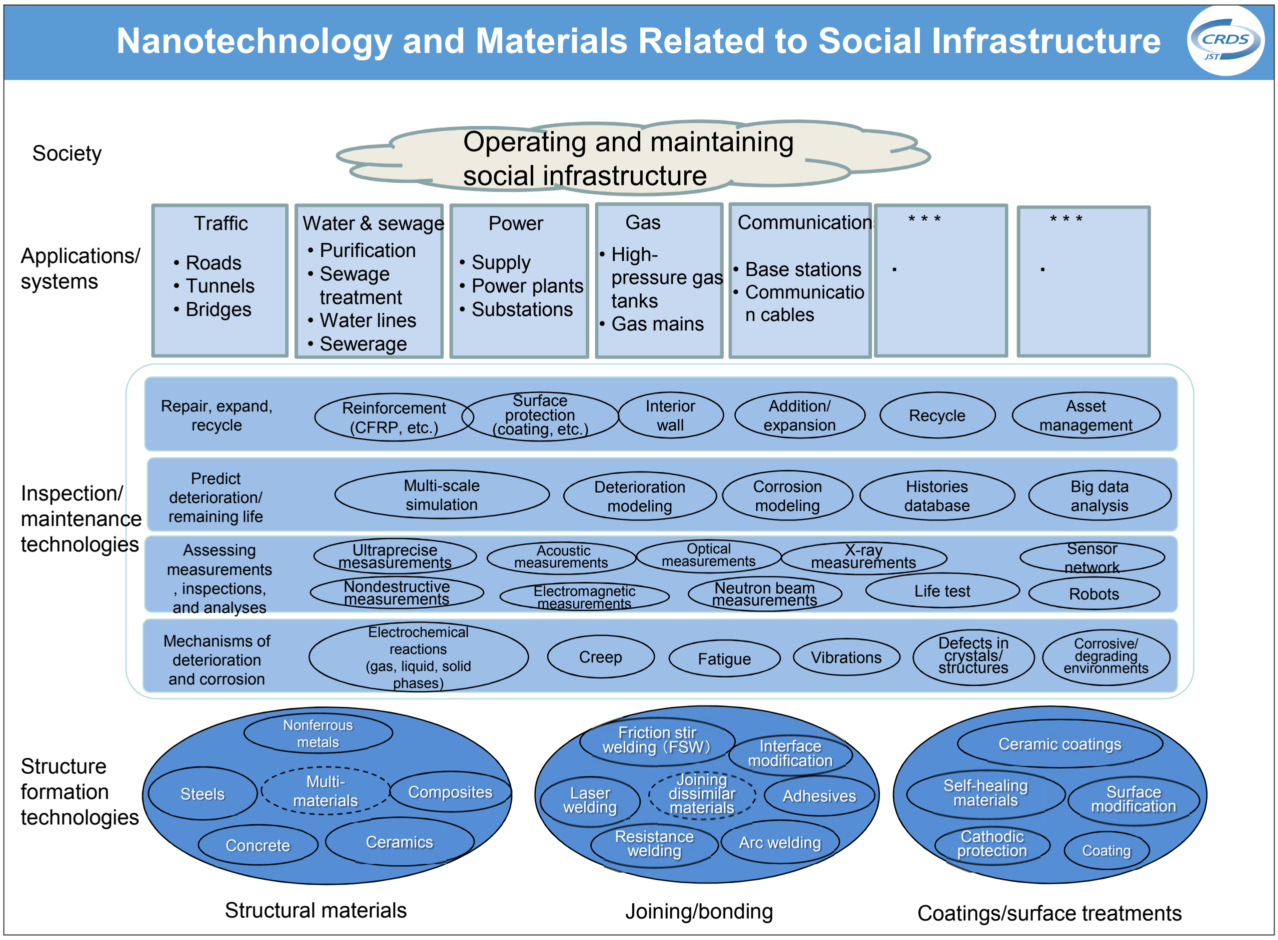


Figure 22. Nanotechnology and Materials Related to Social Infrastructure

- Future direction of R&D

— Engineering that treats old and new structures together

— Designing suitable concrete that expertly uses steel and other reinforcing materials

— Creating numerical models for various corrosive environments to deal with corrosion

— Applying both coating and cathodic protection for effectively protecting steel in offshore structures

— Technologies for predicting corrosion and fatigue cracks beginning in welded parts

— Welding technologies for aging materials

5) Workshop on Strategies for Standardization of Nanotechnology and Research on Safety Evaluation (EHS/ELSI)

The health and environmental effects of new materials and new products produced through the commercialization of advancing nanotechnology and materials and the evaluation and control of risks associated with the novelty of these products are treated as international issues. Studies on the safety of nanomaterials require a large amount of resources because, due to the differences in physical and chemical properties exhibited at the nanoscale from conventional bulk materials and molecules, the biological and environmental effects of nanomaterials cannot be determined from conventional knowledge. Inevitably, such research must be suitably implemented 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 placed on strategic efforts with the goal of commercialization. It is requested that R&D addresses medical assessments and the assurance of scientific reproducibility for establishing methods of risk assessment and risk management, the establishment of a knowledge base for results of risk assessments, and the construction of a framework for public dissemination of information and communication. It will also be important to establish systems for utilizing these tools. Many countries have considered national nanotechnology policies as measures for creating new markets and increased employment, which are the keys to future industry. Safety assessment and management of nanotechnology have been part of public welfare policy, which is intended to alleviate concerns of society about public welfare. In recent years, it appears that nations have become intent on strategically maximizing profits by establishing international standards for nanotechnology safety in order to ensure that the benefits of nanotechnology are invested back into society.

There has been an increasing number of cases in the United States and Europe of nanomaterials being regulated under registration systems for chemical substances, including the European regulation called the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) and the restriction of hazardous substances (RoHS) Directive, both adopted by the European Union. Through about 2014, there had been an ongoing discussion on the definition of nanomaterials in order to clarify what materials should be subject to regulation. These discussions were intended to set standards for determining what materials being manufactured, imported, and sold on the market are “nanomaterials” based on specifications established in 2010 by the International Organization for Standardization (ISO) Technical Committee 229 (TC 229) on nanotechnologies. In addition to this, there has been a trend toward countries and regions establishing their own interpretations of nanomaterials, including the EU’s independent definition and the United States’considerations based on ISO/TC 229. In 2011 the European Commission adopted a definition of a nanomaterial to be “A natural, incidental or manufactured material containing particles, in an unbound state or as an aggregate or as an agglomerate and where, for 50% or more of the particles in the number size distribution, one or more dimensions are in the size range 1 nm - 100 nm.” There have also been moves to establish concrete legal regulations based on the definition of nanomaterial. For example, France has made it mandatory since 2013 to report annually on the quantity and uses for nanomaterials that are manufactured, imported, and distributed in France, and initial results of the declarations have already been reported. Belgium has enforced a registration system for nanomaterials since 2016. There has also been active debate at

REACH on the handling of nanomaterials. The EU has declared that all nanomaterials must be managed in accordance with REACH.

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 (CNT) is considered distinct if it is produced by a different manufacturer or a different process. A proposal was made in 2015 to set criteria for evaluating nanomaterials based on the TSCA SNURs as the standard for permitting the manufacturing and distribution of nanomaterials. The United Nations has initiated discussions on how the Globally Harmonized System of Classification and Labeling of Chemicals (GHS) should apply to nanomaterials.

The Working Party on Manufactured Nanomaterials (WPMN) established under the Organization for Economic Co-operation and Development (OECD) has implemented a Testing Program (sponsorship program) on manufactured nanomaterials since 2007 and is targeting thirteen nanomaterials. The Testing Program has country sponsors and acquires basic information on each nanomaterial, as well as its physical-chemical properties, environmental dynamics, environmental toxicology, mammalian toxicology, and material safety. Japan is a primary sponsor for single-walled carbon nanotubes (CNT), multi-walled CNT, and fullerenes (C60). Test results are compiled in reports called dossiers and summaries of the dossiers. As of the summer of 2016, dossiers had been released for eleven nanomaterials, with summaries being published for four of those.

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) collaborated in examining a wide variety of fields and published a report on policy recommendations. During the period from 2007 to 2010, 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. Scientific research on the effects of nanomaterials on human health funded by the MHLW started in 2003, and multiple research groups have worked on the project. In 2015 the Committee on the Risk Assessment of Chemical Substances (Subcommittee on Hazard Assessments) established under the MHLW Labor Standards Bureau reviewed the results of a two-year inhalation study and genotoxicity study in rats conducted at the Japan Bioassay Research Center on multi-walled carbon nanotubes (MWCNT-7). The committee observed that MWCNT-7 is carcinogenic and mutagenic and concluded that guidelines should be drawn up based on the Industrial Safety and Health Law and that the committee should conduct a risk assessment. 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 evaluating 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 and the project entitled Research Projects for Commercializing Nano-carbon Materials to Realize Low Carbon Society: Development of Fundamental Techniques for Applications of Nano-carbon Materials.

Compared to Europe and the United States, Japan's system for toxicology and safety research is poorly constructed, and its system of collaboration with materials research is particularly inadequate. Safety assessment research in Japan is implemented in parts through projects at various agencies. However, there have been almost no administrative actions toward risk assessment efforts, with only initial studies being conducted on hazards and exposure in 2011. This difference in administrative efforts toward safety management in Japan and overseas could affect the development of nanomaterials and nano-products in Japan and Japan's competitiveness in the envisioned domestic and foreign markets.

R&D on risk assessment for nanomaterials has become broadly divided into research for clarifying the risks of individual nanomaterials, and research for constructing an efficient assessment framework. Japan has taken measures to add individual nanomaterials, such as multi-walled carbon nanotubes (MWCNT-7), to the Guidelines on Preventing Health Impacts from Exposure to Chemicals (Guidelines for Carcinogens), but there exist no general regulations on nanomaterials and the direction of studies on an efficient assessment framework is still unclear. In the meantime, regulatory agencies in the United States and Europe are determining what items need to be reported with regard to nanomaterials and are developing principles for their categorization on the basis of a framework for controlling chemical substances and the circumstances of nanomaterial industrialization in each country and region.

Since it is certain that nanotechnology will eventually have a significant impact on all areas of industry, it is essential that policy measures on collaboration among industry, government, and academy be established in order that the fruits of nanotechnology benefit all of industry and society.

Participants in this workshop reflected on the background and development of ELSI/EHS for nanotechnology, the current status for its implementation in an international framework and collaborative efforts among Japan, Europe, and the United States, and discussed strategic efforts toward responsible research and innovation that include the promotion of science and technology, industrialization, and public engagement. Some of the policy and institutional issues are listed below.

Main Issues of NANO-ELSI / EHS

Summary ; CRDS NANO ELSI/ EHS workshop @March 4, 2016 in Tokyo

Ⅰ. Difficulty of categorizing Nanomaterials toxicities / global issues

- i) Difficulty of biological effects and toxicity identification evaluation
  - Correlation between properties and morphology
- ii) Difficulty of understanding property and character in vivo
  - In actuality micro-aggregate in the body?
- iii) Difficulty of preprocessing of nanoparticle dispersion
  - Nano dispersions technology is also nanotechnology

Ⅱ. Research systems deficiency for Risk Evaluation / Japan issues

- i) A shortage of toxicologists in Japan
- ii) Japan has seen few cooperation work between toxicology and nano- synthesis / nano-manufacturing
- iii) Leadership deficiencies
  - Headquarters is unidentified in industry / university / government

Ⅲ. Strategic policy as emerging technologies

- i) These issues are delicate matters for industries (Especially that is a big burden on the startups)
- ii) Comprehensive strategy of legal controls and standardizations (OECD, ISO, REACH, JIS※)
- iii) Promotion of public Engagement, risk communication and education in a wider stakeholders at an early R&D stage
- iv) Finance / a sufficient amount of budget !

ELSI : Ethical, Legal, and Societal Issues
JIS: Japanese Industrial Standards

Figure 23-1. Main Issues of NANO-ELSI / EHS

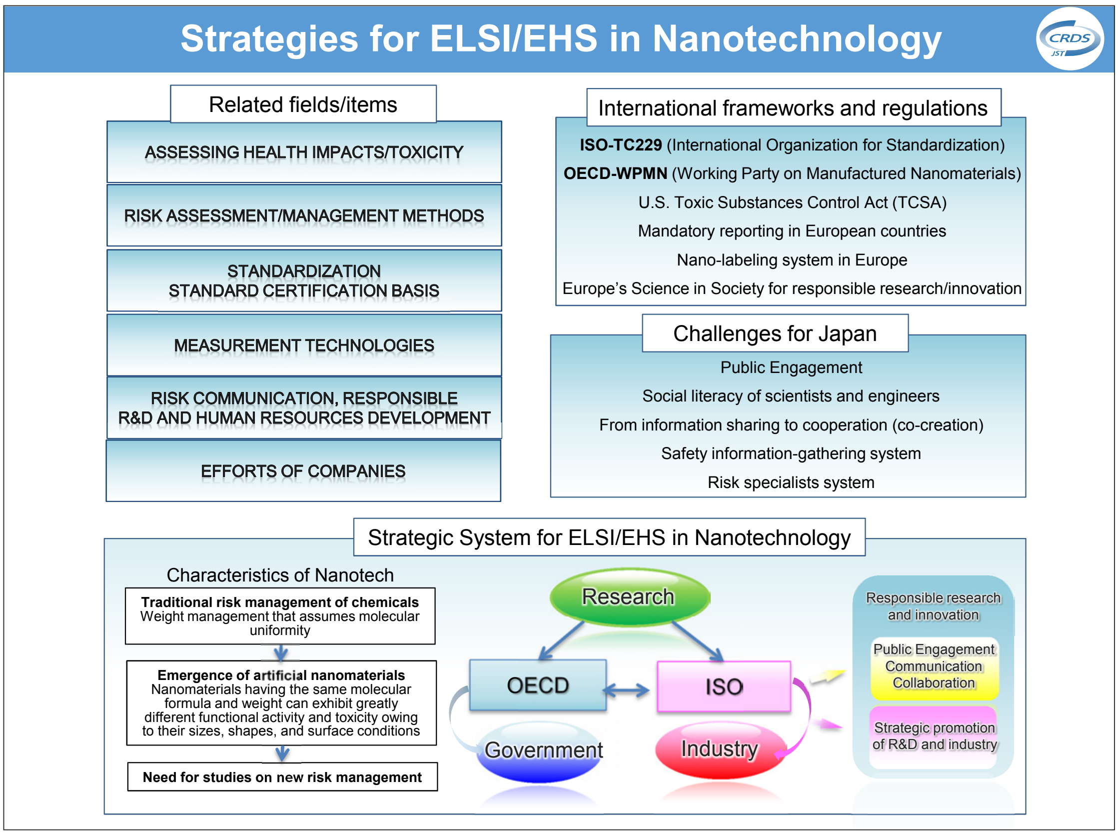
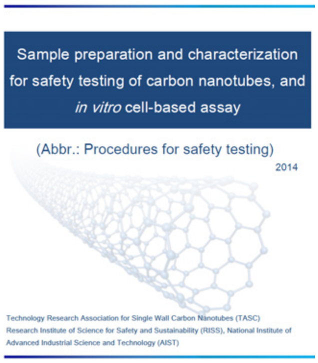
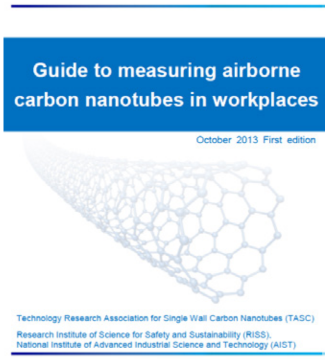


Figure 23-2. Strategies for ELSI/EHS in Nanotechnology

NANO-ELSI / EHS Projects in Japan

NEDO project 2006-2011	Research and Development of Nanoparticle Characterization Methods
METI project 2011-2015	Development of Innovative Methodology for Safety Assessment of Industrial Nanomaterials
Cabinet Office's project 2007-2010	Promotion of R&D on Nanotechnology and Infrastructure Development Related to Social Acceptance
TIA (AIST & TASC)※	Development of exposure assessment and hazard assessment methods to assist voluntary safety management of CNT





※TIA: Tsukuba Innovation Arena for Nanotechnology
AIST: National Institute of Advanced Industrial Science and Technology
TASC: Technology Research Association for Single Wall Carbon Nanotubes

Figure 24. NANO-ELSI / EHS Projects in Japan

3.5 The Role of Industry in Nanotechnology and Materials

Japan's components and materials 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 in the components and materials industry as a whole. According to detailed 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, the global market share for Japanese companies is trending downward, although there are still many Japanese companies that produce relevant components and have a large global market share. Nevertheless, there are still number of 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. They include some materials for LCDs, such as LCD photoresists and color filters, and some materials for lithium-ion batteries.

Generally speaking, nanotechnologies are used in 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 contributions less obvious. An abrupt surge in nanotechnology-related products was observed immediately after they began to appear on the market. According to a market survey conducted by Lux Research Inc., the global market size of nano-enabled products expanded rapidly from US$850 billion to US$1.6 trillion annually during the two years between 2012 and 2014[*]. Below, the automobile is used as a representative example of how nanomaterials are used in industry.

(*) Lux Research Inc., Nanotechnology Update: U.S. Leads in Government Spending Amidst Increased Spending Across Asia (2016)

Over the last ten years, the most significant example of nanomaterials contributing to a new business on a large scale is likely the hybrid vehicle. Although Japanese car manufacturers, including Toyota, Nissan, and Honda, have had a presence in the global market for gasoline-powered automobiles, it was the system of powering a vehicle with both gasoline and electricity, as embodied in the Toyota Prius firstly, that revolutionized the mechanics of automobiles with better gas mileage and lower CO_2 emissions. In 2016 the hybrid car took the largest share of the Japanese market while maintaining a significant share in the global market and expanding its overall market scale. The materials that support this hybrid vehicle, including the high-efficiency motor (high-performance magnets), the rechargeable batteries (nickel-hydrogen batteries and lithium-ion batteries), and power semiconductors used in the power control unit were all introduced newly into the market. Plug-in Hybrid Electric Vehicles (PHEVs) and Electric vehicles (EVs) are following the Hybrid Electric Vehicles (HEVs) and are already commercialized by many automobile makers worldwide. However, since the motors, batteries, and other components in PHEVs and EVs use substantially the same functional materials as HEVs, the market for nanomaterials in automobiles is likely to continue to expand with the addition of PHEVs and EVs. From a strategic perspective in regard to the use of elements in high-performance magnets, Honda and Daido Steel jointly developed a neodymium magnet free of heavy rare-earth metals. The magnets were incorporated in hybrid vehicles in 2016. Automakers have been transitioning their rechargeable batteries from nickel-hydrogen to lithium-ion batteries. However, lithium-ion batteries use flammable organic electrolytes, which cause some concerns about safety and also have limitations in energy density. Consequently, the batteries are heavier and bulkier, requiring more space in the hybrid cars now entering the market. From the perspectives of safety and the potential for performance improvements, there is anticipation for the future use of next-generation batteries, such as all-solid-state and metal-air batteries. Since the cathode materials, anode materials, and solid electrolytes in these batteries would require combinations that include new materials, many companies in addition to automotive makers are actively studying such materials. Obviously, making the frames of cars lighter is essential for improving fuel efficiency, and an industry-government-academia collaboration project on that subject is being carried out under the NEDO program Innovative Structural Materials R&D (2014–22). The project targets not only materials for cars, but also a wide range of transport vehicles and structural materials and is expected to produce many practical applications.

On the topic of vehicle exhaust, stricter environmental regulations are predicted internationally for the elimination of NOx, a harmful component in diesel exhaust. Automakers, catalyst manufacturers, and other companies are actively engaged in R&D to develop a cheap and reliable method of removing this component. The market is eagerly awaiting a selective reduction catalyst that can achieve better performance with reliable technique. Since we will likely see further motorization in Asia, stricter environment regulations, and more momentum toward curbing global warming, the market for automotive exhaust gas catalysts will likely continue to expand, requiring further innovation with nanomaterials.

3.6 Policies for Promoting R&D and Innovation around the World: Constructing an Ecosystem for R&D

Advanced technologies have become increasingly sophisticated, complex, and interdisciplinary. Therefore, observation, assessment, and control of phenomena at the atomic and molecular level are especially necessary in the field of nanotechnology. It is difficult for individual companies and research institutes of any country to maintain a group of researchers whose expertise covers all of these specialized fields, expensive equipment for experiments, and technical specialists who can fully utilize such equipment.

At the same time, competition in R&D has intensified on a global scale, with growing demand for accelerated development. Around the world, research is being conducted more and more at hub-type open innovation centers that provide the following advantages.

- Cost and risk sharing among multiple companies and research institutes (reduced development costs and reduced risk)
- Bringing diverse specialists together in one location
- Public investment and support in a shared R&D infrastructure and fundamental technological development
- Mutual use of intellectual property

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. Rather than simply investing in R&D aimed at producing innovation, it is important to establish operation and investment strategies throughout the entire value chain in order to increase return on R&D investment in the mid-to-long term. This means that strategies for updating to the latest instruments and equipment, for intellectual property, for standardization, and for public dissemination of new technologies must be taken up together.

● Large-Scale Nanoelectronics Research Centers around the World

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

The Tsukuba Innovation Arena (TIA) was launched in Japan in 2010. TIA is an undertaking operated primarily by AIST, NIMS, the University of Tsukuba, the High Energy Accelerator Research Organization (KEK), and the University of Tokyo in collaboration with the Japan Business Federation, and is an effort to construct an internationally attractive nanotechnology research center and to enhance Japan's accomplishments as a producer of cutting-edge products. With the addition of the University of Tokyo in 2016, the hub changed its name from TIA-nano to simply TIA and expanded its research activities to include nanobiotechnology and data-driven science, while continuing to conduct research on nanotechnology. Originally, six priority research areas (nanoelectronics, power electronics, N-MEMS, nano-GREEN, carbon nanotubes, and nano-material safety) that directly lead to commercialization were established as the core research domains at TIA-nano. The facilities also included three core infrastructures for the fabrication and evaluation of prototype devices, the open use of cutting-edge nanotechnology equipment, and a framework for promoting human resource development. Beginning from 2016, these research areas were reorganized into three platforms (the systems and integration platform, advanced material platform, and basic resource platform). The system and integration platform includes the research areas of nanoelectronics, power electronics, and MEMS and the advanced material platform includes the research areas of carbon nanotubes and nano-GREEN, with both platforms implementing projects related to their corresponding areas in collaboration with businesses. The basic resource platform includes the area of light/quantum measurements, human resource development, and open research facilities and works to develop advanced measuring technologies, help researchers develop their skills and advance their careers, and assist in research. Also in 2016, TIA launched the collaborative research program Kakehashi for researchers in the five core institutes to jointly explore new research themes having the potential to spark innovation. Many fascinating new research themes have been proposed, with some expected to be selected for actual research projects. Projects utilizing the TIA hub to produce results include the FIRST, SIP, and ImPACT programs under the Cabinet Office and various national projects under MEXT, METI, and NEDO (a total of 34 projects as of 2015). With 145 companies and more than 600 outside researchers participating in projects at TIA during 2015, the function of TIA as an innovation hub is steadily improving. There have also been cases of research projects for promoting open innovation being operated in a self-sustaining manner through funds received from member companies in addition to public funding, and specifically the NIMS Open Innovation Center (NOIC) in the nano-GREEN area and the Tsukuba Power-Electronics Constellations (TPEC) in the power electronics area. Efforts have also been made to promote the creation of new corporate-driven projects by providing single-walled carbon nanotubes and composite materials and by loaning companies use of a CNT manufacturing plant.

● Nanotechnology Platform Japan

Since 2012 a ten-year project called Nanotechnology Platform Japan has been administered in Japan as an extension of two MEXT projects: the Nanotechnology Support Project (2002–6) and the Nanotechnology Network (2007–11).

Its goal is not only to increase the efficiency of R&D investments by concentrating expensive cutting-edge equipment in various regions throughout Japan 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 striving to develop groundbreaking materials and devices in three technological areas (Advanced Characterization Nanotechnology Platform, Nanofabrication Platform, and Molecule & Material Synthesis Platform). In this program, 38 facilities from 26 member institutes and universities are joined and establish one single structure for "Share-Use Cutting-Edge Facility for Nanotechnology" The Platform constitutes a system for providing users highly technical services at an optimal location. 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 with potential users including young researchers and local small and medium-sized enterprises.

In 2016 annual usage of the Platform had grown to approximately 3,000 uses. The entire Platform is operated under a combination of the MEXT project budget (1.7 billion yen in 2016), revenue from usage fees, and badgets borne by the member institutes. The Platform provides development support specific to industries, the use of expensive facilities for university researchers on a low budget, and access to the skills, knowledge, and expertise of specialized technicians. By producing tangible results in which users can leverage the Platform for their own purposes, a new ecosystem for R&D is being cultivated. Through the Nanotechnology Platform network, there have been cases in which an issue could not be solved at one facility but the user was referred to another facility in the network that was able to come up with a solution. This is a mechanism unique to Japan. The strengths of the Platform lie not just in the provision of facilities, technologies, and other services, but in the accumulation of technical knowledge, examples, and solutions itself. It is a wellspring of value creation. Particular advantages can be found in the central function of the network, such as its much-improved one-stop website that incorporates usage examples and other knowledge, and database of facility information. This type of network provides an R&D Infrastructure that can support all future national projects and industry-academia collaboration not just in the nanotechnology field, and can maximize return on R&D investments.

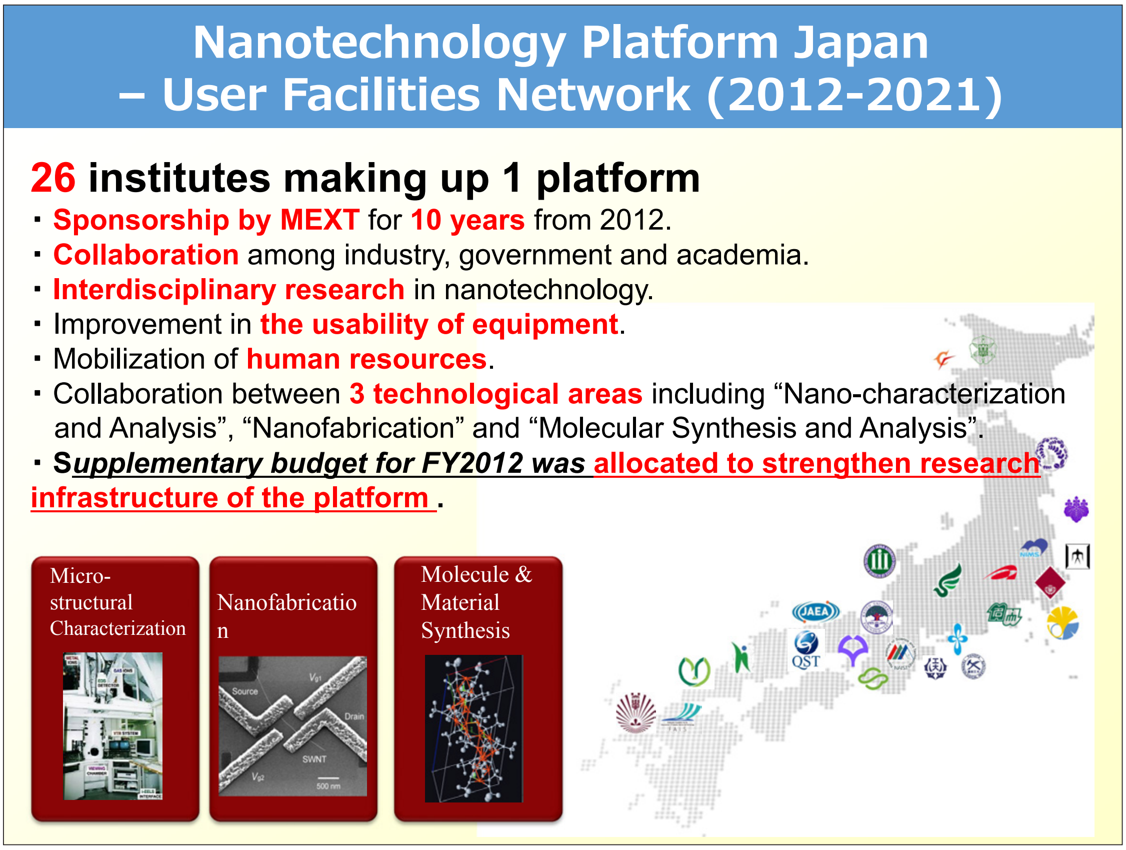


Figure 25-1. Nanotechnology Platform Japan– User Facilities Network (2012-2021)

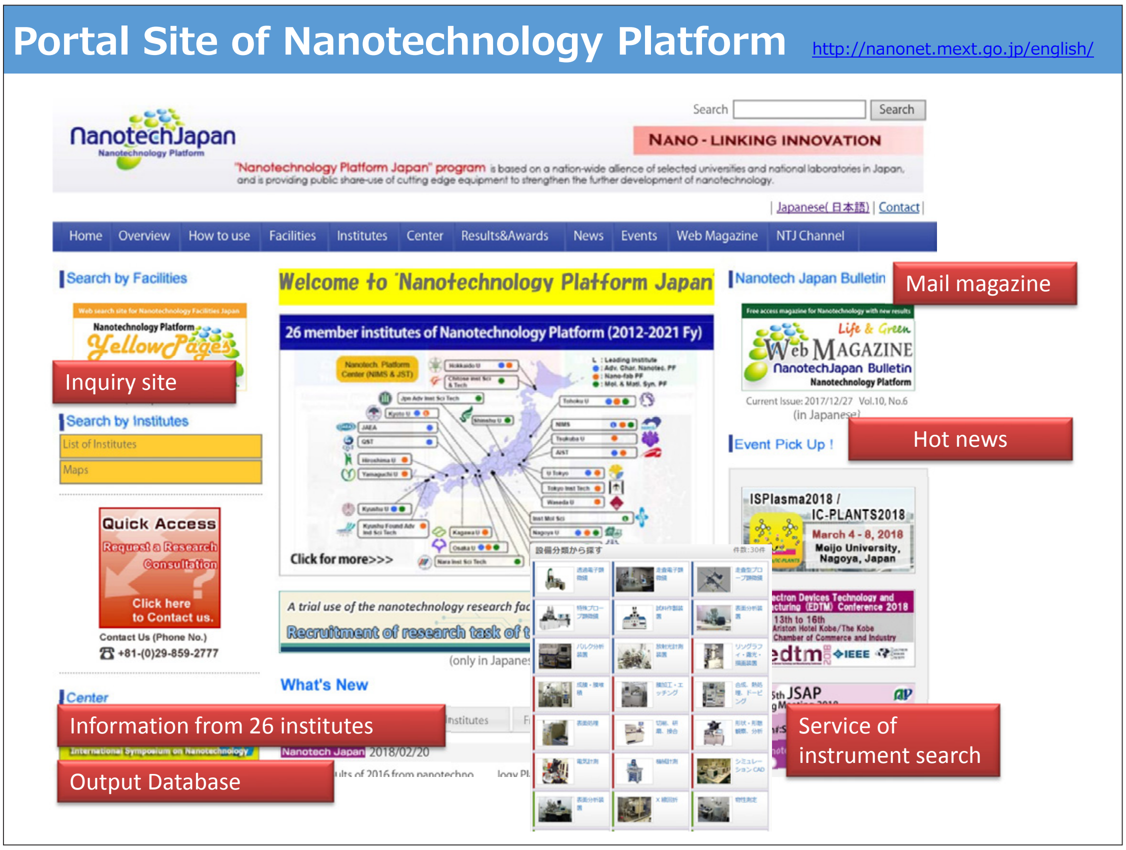


Figure 25-2. Portal Site of Nanotechnology Platform

4 Future Direction and Challenges

This section discusses what role nanotechnology and materials can play in the future to solve social issues.

• The Environment, Energy, and Social Infrastructure

With all the safety concerns it brings, nuclear power generation is not likely to be looked to for the bulk of Japan's future energy supply. On the other hand, the issue of global warming caused by fossil fuel energies is increasingly serious. Against this background, 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-combustion power generation based on, for example, combined-cycle operation and high-temperature combustion operation. For high-efficiency fuel-combustion power generation, it is important to develop high-temperature-resistant materials and coating materials for increasing combustion temperature.

With the increasing use of renewable energy, whose electric energy yield is dependent on weather conditions, using surplus energy to generate hydrogen will become significant economically. Further, generating hydrogen and oxygen from water directly and efficiently may no longer be a fantasy in the future with artificial photosynthesis technology. 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 perspective of energy utilization, it will be necessary to develop energy-saving technologies, and specifically solid-state lighting, low-power 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. Above all, it will be important to reexamine our lifestyles, 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. Looking at the world, one sees that the amount of drinking water is limited. Urgent issues therefore include generating drinking water from seawater and wastewater; cleaning produced water in large amounts containing radioactive or toxic substances, which results from shale gas production; and developing low-cost mass-producible adsorbents and purification membranes.

These social or technological issues concerning the environment and energy will be difficult to solve in a specific academic discipline or technological field, but will require an interdisciplinary approach and collaboration among multiple fields.

One significant social issue in Japan is its aging social infrastructure. Some of the bridges, tunnels, roads, and other infrastructure that Japan built in a period of rapid economic growth are now more than fifty years old. Extending the life of this aging infrastructure through efficient inspections and reviews and systematic repair and renewal is essential. R&D from a perspective of nanotechnology and materials will be important for addressing this issue.

For efficient inspections and reviews of social infrastructure, monitoring with sensor systems and understanding and modeling time-dependent changes in materials (structural changes, corrosion, etc.) at the microscopic level will be important for predicting the remaining life of infrastructure. Here, miniature ultrasonic sensors will be useful for examining the interiors of structures, while corrosion sensors will be helpful for examining surface conditions. Synchrotron radiation and other technologies can be used to observe atoms and other nanoscale phenomena in the material itself, deterioration at bonded interfaces, and corrosion on surfaces of various structures to enhance our understanding and construct models of these mechanisms. The models can serve to develop simulation techniques for use in predicting deterioration and remaining life.

Techniques important for the repair and renewal of infrastructure include welding, joining, bonding, corrosion protection, painting, and coating, but it is also important to control the materials at surfaces and bonded interfaces on the nanoscale level. For example, when welding new steel material to old steel infrastructure, it is essential to know the precise composition and surface conditions of the old steel material. Applying welding conditions that are inappropriate for the new steel material may lead to structural defects and significant changes in chemical composition. This will require techniques for assessing old steel materials and for simulating welding that accounts for changes in composition and stress. When protecting against corrosion, if one accurately knows the environment in which the infrastructure is installed and the composition and degree of deterioration in the structural materials, it is possible to apply paint or coating using materials and processes that are suited to these conditions. For this, techniques for analyzing materials, sound coating technologies, and technologies for simulating corrosion will be essential.

The technologies described above for operating and maintaining social infrastructure are closely connected to the increasingly necessary technologies for constructing lightweight aircraft and automobiles. Along with this trend to develop multi-materials that combine such diverse materials as steel sheets, aluminum, magnesium, titanium, and CFRPs in particular, technological development from the perspective of nanotechnology and materials will be important.

● Life Sciences and Health Care

Recent progress in the life sciences is remarkable, as witnessed in the sequencing of the human genome, the generation of iPS cells, and advances in genome editing and cryo-electron microscopy. Extensive knowledge in life sciences has been accumulated by arranging organism-derived substances including DNA, proteins, and cells on semiconductor chips and precisely measuring and accurately manipulating these substances. These advances have been enabled by integration of the cutting-edge semiconductor technologies and optical technologies, leading to high-expectations for innovations resulting from this integration.

For the individual, it is desirable to detect signs of illness at an early stage and to take preventative measures before actual medical treatment is necessary. From the perspective of health management, there is a need to develop sensing devices that easily collect samples from the breath, and devices capable of more rapidly and sensitively detecting organism-derived substances in bodily fluids, such as urine and blood, for the early detection and diagnosis of physical anomalies. In that sense, it is hoped that these semiconductor chips will be able to detect biomarkers indicating certain diseases with great sensitivity. Incorporation of semiconductor chips capable of highly sensitive detection into ultra-small wearable devices will enable daily health monitoring and will lead to advances in preventive medicine. If the range of detectable objects is expanded to pathogens such as viruses, it would be possible to build a system that constantly monitors pathogens present in various environments in order to 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, exosome, a single cell, or a single molecule on an artificial microstructure (or even a 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. With the ability to provide new added value on semiconductor chips, this research should produce great opportunities for semiconductor business.

There is also a study on utilizing nanoparticles as transporters in Drug Delivery System (DDSs) in order to administer medical treatment by efficiently delivering drugs to the affected areas. Nano-DDSs are considered essential for the practical use of nucleic acid medicine. It is therefore important 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 in theranostics for the integration of diagnosis and treatment. Also, the 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 applications in regenerative medicine and as screening tools 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 for forming three-dimensional cell aggregates that have complex structures and functions are quite important for not only regenerative medicine but also drug discovery. Here, too, integration of life sciences with nanotechnology and materials is needed. Connecting such integration to innovations in diagnosis, medical treatment, and drug discovery is an important challenge in medicine.

From the standpoint of the patients' quality of life, improvements are needed for many of the medical materials currently in use. It is necessary to continue developing materials with good biocompatibility for the intended purpose and processing technologies that apply nanotechnology.

● Information, Communications, and Electronics

With the arrival of the Post-Moore Era, it will be necessary to explore the possibilities of electronics from wholly new perspectives and under new concepts. A focal point of this period will be IoT and AI technologies that form the core of information society in the future. Recently there have been significant developments in artificial intelligence, deep learning, quantum computing, robotics, and sensor technology. It is desirable that the large quantity of IoT devices in our lives be able to process large quantities of data at a high speed using little energy. This will be achieved with nanoelectronics, and in particular will require a system of integrated nanoelectronics that includes not only ultra-low power semiconductor chips, but spintronics for accumulating information, wireless and photonics technologies for transferring information, various sensor devices based on MEMS technology, and display technologies founded on organic electronics.

Nanoelectronics will need to play a major role in realizing a super smart society in the IoT/AI age. Advances in nanoelectronics are thought to occur in phases: the pursuit of extreme miniaturization of devices (Progress Nano); the emergence of multiple functions based on the introduction of new materials together with many functions produced by light, spin, biology, and MEMS (Fusion Nano); and the application of nanotechnology to high-resolution displays, wearable devices, and the IoT (Systems Nano).

Nanoelectronics plays a major role during this process, as illustrated by the following two examples. The first is the importance of nanoscale thermal control. At the nanoscale level, electrons, spin, photons, phonons, and so forth, which are quantized, play an important role to produce various functions. Research is being actively pursued on theoretical approaches or on measurements and simulation technologies for electrons, spin, and photons, as they are leading actors in various physical phenomena. Phonons, which are related to heat phenomena at the nanoscale, also participate in extensive physical phenomena, but in more of a supporting role. Thus, research is lagging behind in terms of unified approaches to theoretical or measurement studies of phonons. In terms of the application of nanotechnology to various devices, device performance is significantly restricted by heat generated from electrons moving through channels, as seen in micro-CMOS devices. In addition, many different kinds of materials are used in the microstructures of semiconductors, leading to complex phonon transmission. There is thus a risk of creating hot spots in the devices. For these reasons, nanoscale thermal (phonon) control, or "phonon engineering," will only continue to increase in importance. What we need are comprehensive design methods for nanoscale structures that take into account such factors as electrons, spin, photons, and phonons.

The second example is a solution for the data input/output bottleneck occurring as the scale of circuits on system LSIs continues to be increased to improve data processing capability. Consequently, there is great interest in 3D integration technologies for achieving higher bandwidth for data transfer, including Through-Silicon Via (TSV), which are vertical interconnects that implement input/output through electrodes that vertically penetrate a multilayered Si semiconductor chip, and magnetic near-field coupling for implementing input/output between chips through magnetic field coupling. These technologies have the capacity to reduce power consumption for communications to 1/1000th that of conventional technologies. By employing these technologies in chip communications between system LSIs and memory, the I/O bottleneck can be eliminated, leading to the development of low-power, high-performance computers.

● Design and Control for Materials and Functions

In the Fifth Science and Technology Basic Plan, Japan established nanotechnology and materials as "fundamental technologies that are Japan's strengths, which form the core of new value creation." The Basic Plan lays out basic concepts on design and control for materials and functions, including element strategy, molecular technologies, and nanogap/nanospace control, that have the potential to produce breakthroughs in material development in order to fill a wide range of needs in society and industry, and to produce disruptive innovation. Here, combining the power of various dissimilar fields will be indispensable, as existing disciplines such as chemistry, physics, and materials science cannot take on these challenges alone. To achieve this, it is necessary to tear down the traditional vertical divisions between disciplines and establish a framework whose policies and leadership vigorously promote integration and collaboration among dissimilar fields. In recent years, JSPS and JST have gradually encouraged more integration and collaboration within its large-scale projects. However, industry-academia collaboration is still lacking. It is necessary to encourage integration and collaboration throughout the entire field of nanotechnology and materials.

Recent advances in ICT are significantly changing methods of R&D on nanotechnology and materials. As improvement in the performance and reliability of devices is pursued under these circumstances, materials supporting these qualities are becoming more complex and diverse. At the same time, necessary functions must be realized by combining chemical elements that exist abundantly 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. Owing to dramatic improvements in the performance of computers and advances in information technology, researchers around the world are taking a more proactive approach toward discovering systematic rules on the performance and functions of materials based on the large quantity of materials data in order to develop materials efficiently within a short period of time. Accelerating this trend requires not only cutting-edge information technology that enables researchers to organize enormous amounts of data on materials, to search for necessary information, and to discover new knowledge, but also researcher groups who utilize these tools and develop new materials. Materials informatics is indispensable for maintaining and strengthening our development capabilities for materials, the lifeblood of industry.

Examples of Challenges in Nanotechnology and Materials

CRDS selected the following ten issues as current challenges in nanotechnology and materials.

(1) Separation Technologies

Realization of high precision material separation and purification technologies with low energy consumption.

For this purpose, it will be key to conduct R&D on materials and systems with separation and absorbent capabilities in a wide range of fields, including energy-efficient separation in chemical processes, removal of environmental pollutants, separation and storage of hydrogen for the coming “hydrogen society,” separation of mineral resources, and separation of organism-derived substances such as cells and bioparticles. In R&D aimed at meeting these objectives, it will be necessary to make full use of the latest new materials and nanostructure control technologies, as well as the latest developments in measurements and simulation.

(2) Biomaterials and Devices for Controlling Interactions between Living and Artificial Materials

R&D on devices for visualization and analyses of nanoscale interactions between artificial materials and organism-derived materials or cells in vivo, and on materials for controlling these interactions.

Cells, proteins, and DNA are arranged on semiconductor chips and in microfluidic channels and are utilized in studies on controlling interactions at the molecular level and screening for diagnoses and drug discovery. Cutting-edge technologies on semiconductor microfablication and imaging will lead to the development of new biomaterials and devices that will be vital to meet needs in the health care sector.

(3) Development of Super-Composite Materials through Nanodynamic Control

Establishment of novel academic foundation by accumulating new knowledge on the behavior of molecular assemblies at the nanoscale in response to macro-mechanical stresses. By expanding from this base into R&D on dynamic behavior at the nanoscale, such as stress concentration phenomena, fracturing and self-healing phenomena, rheology, and the dynamic behavior of functional molecules in soft materials, super-composite materials that exhibit functions not achievable in existing composites will be produced.

(4) Innovation in IoT/AI Chips

Realization of such novel functions as sensing, next-generation computing including neuro and quantum computing, networks needed in the IoT/AI age by using electronic systems based on semiconductor chips.

These functions will be expanded to develop the creation of safe and secure environments, and new services coming from health management and diagnoses, and self-driving vehicles, for example. As device miniaturization becomes more difficult in accordance with the limitation of Moore's law, innovation of devices with new operating principle, computer architectures, and packaging technologies become key to develop next-generation electronics.

(5) Nano-IT-Bio-Mechanical Integrated Manufacturing

Artificial reconstruction of structures, functions, processes and driving mechanisms by learning how organism realize them with low energy consumption.

Studies will be conducted to realize bio-inspired technologies employing 3D printing as well as small, lightweight, high-output power autonomous and cooperative robots. The realization of these technologies will require technologies for modeling biological mechanisms, enclosures formed of soft materials that will allow coexistence with humans, and AI chips for recognition and decision-making.

(6) Integrated Design and Control Technology for Quantum Systems

Construction of an integrated control technology quantum-mechanically integrating not only electrons, photons, and spin, but also phonons, which are the origin of heat.

Phonon engineering is needed to control the inevitable heat generation problems in accordance with advances in ICT through these origins of heat. Further, the emergence of topological materials has led to the discovery of new quantum states combining electrons, spin, and phonons. The development of new materials and a technology for controlling these quantum states is expected to expand their applications into quantum computing and spintronics.

(7) Operando Measurements

Exploration and creation of new materials and devices, development of batteries, catalysts, and elucidation of living phenomena by application of operando measurements utilizing the state-of-the-art measurement technologies to analyze a broad range of targets, from materials to living organisms.

By measuring materials in catalytic reactions and in semiconductors and batteries in their actual environment of operation, measuring living cells and biological tissues, and directly observing minute-to-minute operations and continuously changing phenomena, we can discover correlations between the observation targets and their functions.

(8) Data-Driven Materials Design (Materials Informatics)

Novel approach for exploration and design of novel materials making full use of data science to reduce the cost and time which is thought to take 30 years from discovery to implementation of new materials.

A new approach that coordinates data science with artificial intelligence, machine learning, and materials science is needed to meet expectations for increasingly diverse and complex high-performance materials.

(9) Strategic Measures on ELSI/EHS for Nanotechnology

Aspects of ELSI/EHS for nanotechnology must be treated as international issues. It is important that all sectors cooperate and collaborate, particularly in the sharing of risk assessment data and protocols, in order to maximize the benefits to society.

(10) Forming R&D Centers and Platforms to Absorb the World's Knowledge

In order to support leading R&D on nanotechnology and materials, it is critical to install and upgrade cutting-edge facilities and then gather together the knowledge in the world. Such investments are difficult to maintain at individual companies and research institutes. The key is to form a global R&D platform for maximizing the cost-effectiveness of R&D.

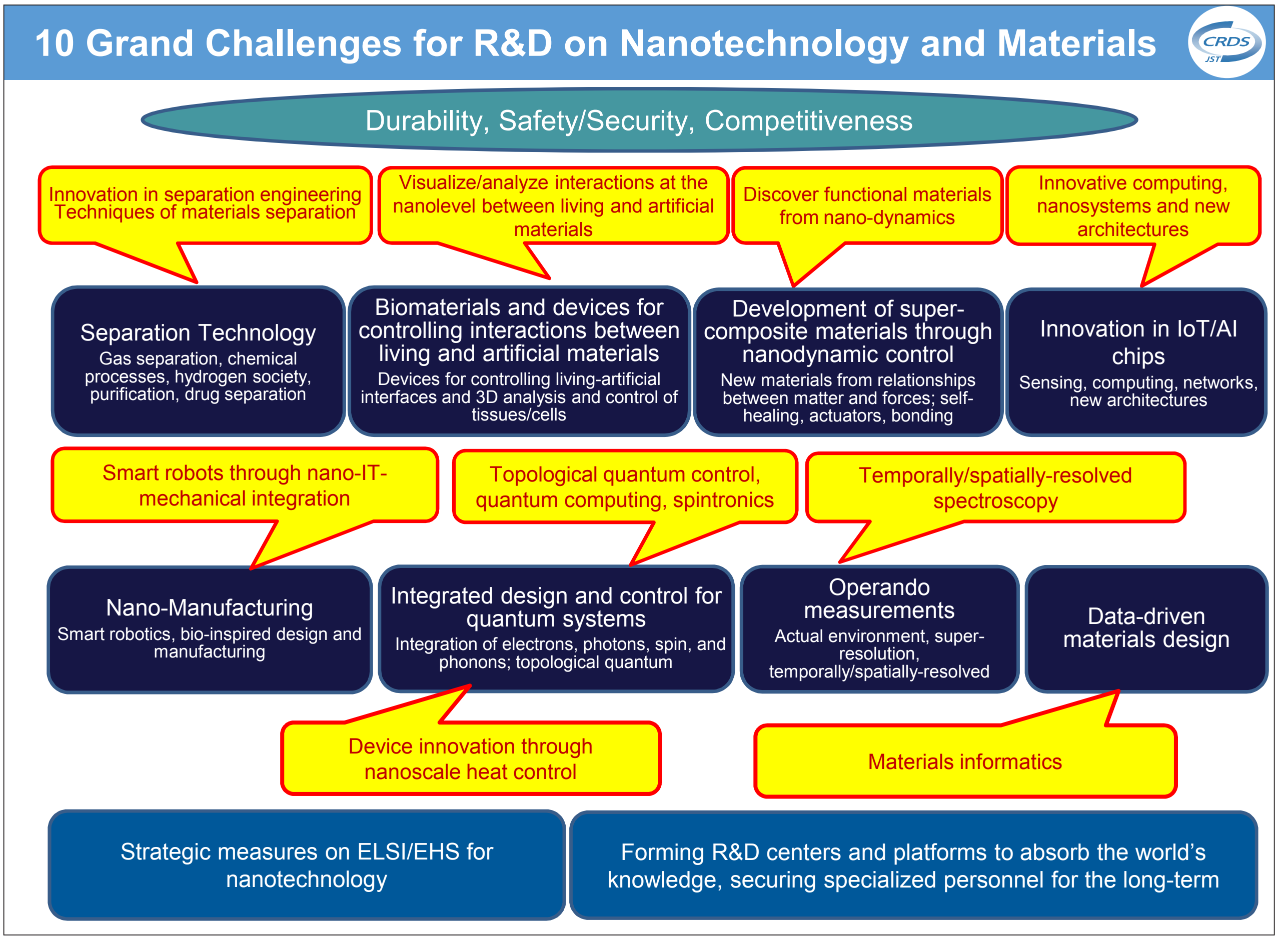


Figure 26. 10 Grand Challenges for R&D on Nanotechnology and Materials

While industrial manufacturing constitutes part of the global value chain, it is senseless to discuss industrial competitiveness from the exclusive viewpoint of one nation. Here, we will keep in mind that technologies developed by Japan produce essential components that are furnished to the world in the form of competitive products. Among the technological areas to which nanotechnology and materials apply, nanoelectronics such as electronic components and semiconductors; energy-related components such as batteries; sensors; mechanical devices; chemical products; and advanced materials are all sources of industrial competitiveness. The issues here lie in how competitiveness at the component and device level translates to competitiveness at the system level with higher added value, and how quickly results at the fundamental research level can be translated into prototypes and subsequently competitive applications and products. For this reason, an open innovation research framework establishing collaboration among industry, government, and academia is expected to play a major role. Operating such a framework requires strategies on intellectual property, standardization, and internationalization; an assembled group of researchers and technical experts in dissimilar fields; and a collection of technologies possessed by the participating institutes, and requires advanced administration and management skills. In the final stage, industry should play a central role and establish the framework to produce profit. However, in the initial stage, the infusion of triggering capital as a government policy is necessary to construct a management structure and establish fundamental technologies.

Figure 27 is a conceptual drawing of an open innovation R&D framework for next-generation semiconductors targeting innovation in IoT/AI chips in Japan proposed in this report. The R&D framework includes a Nanotechnology Platform (Nanotech PF) configured as a consortium of universities and national research institutes that develop and evaluate component device and materials technologies; a Next-Generation Semiconductors and Integrated Systems Platform (Next-Generation Semiconductors PF) for implementing ideas on new materials, devices, and architectures at the chip level; and a mass production line operated by domestic and foreign industries for realizing commercializing prototype chips. Nanotech PF is a MEXT program that provides users from industry, government, and academia with research support and cutting-edge facilities located at universities and national institutes throughout Japan, and covers such technical areas as nanofabrication, microstructural characterization, and molecule and material synthesis. Activity at Nanotech PF began in 2012, but usage among industry increased abruptly in recent years, with many successes reported. It is hoped that the new framework will allow Nanotech PF to respond to requests from Next-Generation Semiconductors PF for the development of new materials and the structural characterization of new materials and devices, and that, conversely, Next-Generation Semiconductors PF will respond to requests from Nanotech PF for integrating component technologies into systems to achieve improved functionality and commercial viability. The Next-Generation Semiconductors PF will manufacture prototype semiconductor chips replete with new ideas and will accumulate any intellectual property on the resulting circuit designs in an on-site IP bank for reuse. The Next-Generation Semiconductors PF will also be equipped with electronic design automation (EDA) tools to design circuits based on new devices and new architectures. The platform will establish a system of shared facility use, allowing researchers to use industrial production lines when a standard process required for chip prototyping is unavailable, thereby providing full process chip prototyping. The Next-Generation Semiconductor PF has to construct the experimental fabrication line which is compatible with collaborating industrial production lines, and to adapt to finer advanced processes for development when necessary. Technologies developed through this platform will be transferred to the semiconductor mass production lines of the collaborating industries. The human resources developed through these R&D processes will lead the next generation of researchers. Through these efforts it is hoped that we can construct an ecosystem for R&D that develops new ideas on materials, devices, and architectures produced by universities and national institutes into commercial products.

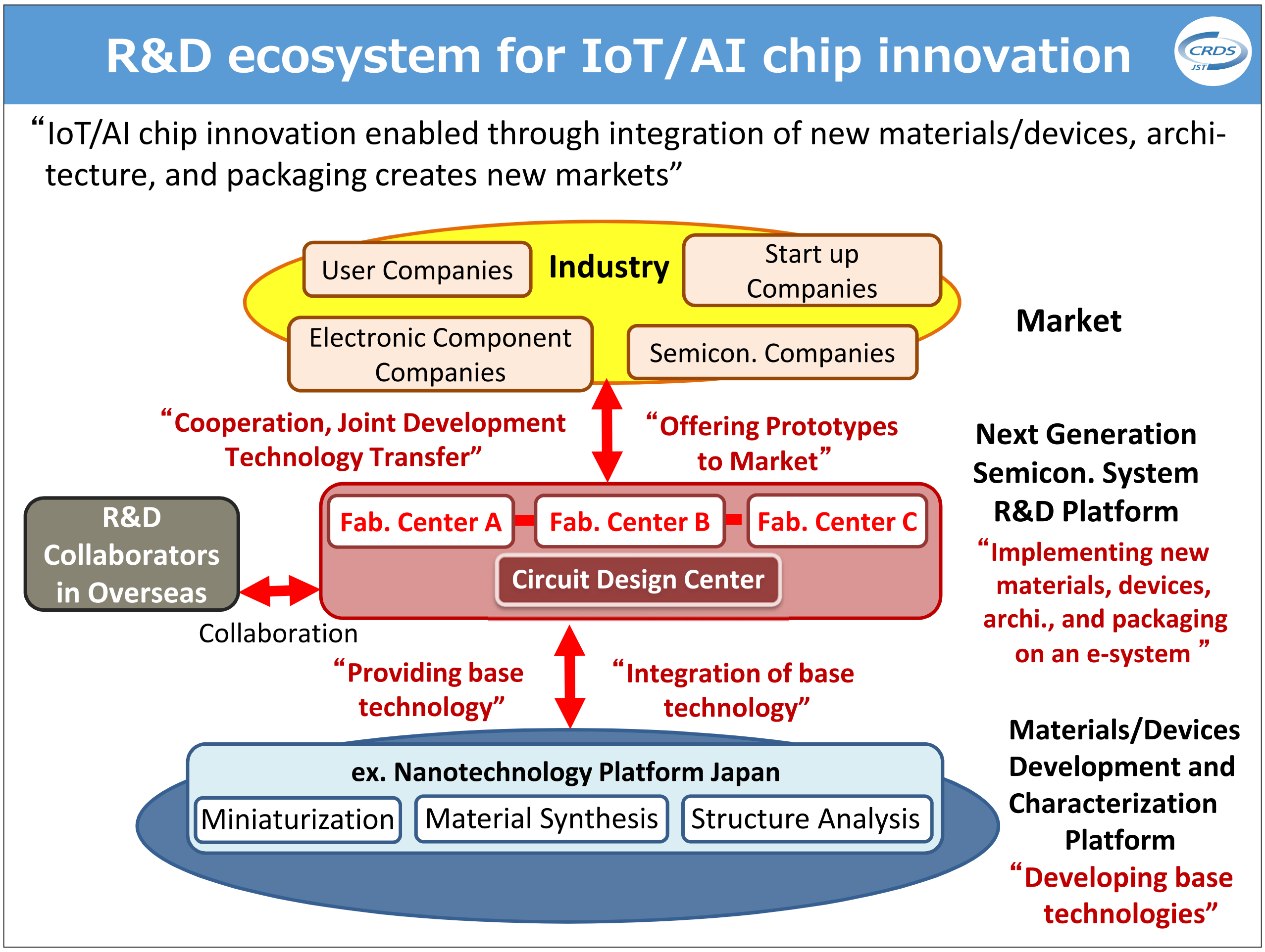


Figure 27. R&D ecosystem for IoT/AI chip innovation

■ Contributors of Nanotechnology and Materials R&D in Japan (2018): An Overview and Analysis ■

Jun'ichi Sone	Principal Fellow
Toshiki Nagano	Fellow / Unit Leader
Aya Araoka	Fellow
Katsuaki Sato	Fellow
Nobuaki Onagi	Fellow
Satoshi Miyashita	Fellow
Seiichiro Kawamura	Fellow
Tetsuya Ito	Fellow
Tomohiro Nakayama	Fellow
Toshio Baba	Fellow

CRDS-FY2017-XR-02

Nanotechnology and Materials R&D in Japan (2018): An Overview and Analysis

March 2018
ISBN 978-4-88890-583-1

Nanotechnology / Materials Unit,
Center for Research and Development Strategy, Japan Science and Technology Agency

K's Gobancho, 7, Gobancho, Chiyoda-ku, Tokyo 102-0076 JAPAN
TEL: +81-3-5214-7481
FAX: +81-3-5214-7385
http://www.jst.go.jp/crds/en/about/index.html

ISBN 978-4-88890-583-1