A Future Society Built by Nanotechnology

By Watanabe Makoto

Last year was the dawn of nanotechnology in Japan. Before then, Japan had become involved from an early stage in advanced research into nano fields including a nano-mechanism project in 1985, the discovery of carbon nanotubes by Dr. Iijima Sumio in 1991, and atom technology in 1992. In addition to such work, the country was also pursuing the development of nano-level technology in fields such as electronic devices and materials. It was only last year, however, that these works were widely recognized as the keyword nanotechnology in Japan.

The major factor was the National Nanotechnology Initiative (NNI) announced in the United States last year by former President Bill Clinton. NNI is using easily understood catch phrases and concepts that impress the general population: a sugar-cube-sized memory that can store all of the Library of Congress' information, material lighter yet ten times stronger than steel, and chips that will accelerate computer processing speed by several million times. Under this publicity campaign and with meticulous analysis carried out over three years, the United States has increased the NNI budget by 83%, from US$270 million to US$495 million, and it seems that the Bush Administration is maintaining the same position.

Control of material down to the nano-level of one-billionth of a meter enables dramatic advancements in material functionality and properties including the output of extremely clear light and improved strength and durability. At the same time, achieving high functionality at nano-size will help realize an environmentally-friendly society by vastly reducing the use of energy and resources. Nanotechnology has the potential to revolutionize society and production systems, and for the economic world as well, it is now considered a key technology for 21st century industry.

It is no surprise that those involved with nanotechnology in Japan were shocked by and envious of the U.S. government's top-down measure of bold, concentrated investments in nanotechnology. Japanese industry also was alarmed by such strategic involvement by the United States. In response, in June last year, we established the Expert Group on Nanotechnology under the Japan Federation of Economic Organizations' (Keidanren) Committee on Industrial Technology to start studying nanotechnology. This led us to realize once again the importance of nanotechnology. According to discussions held at Keidanren, preliminary estimates by Hitachi Research Institute place the market scale for nanotechnology at ¥27 trillion in 2010. (Figure 1)

During the course of this study, Keidanren announced its "Nanotechnology That Will Pioneer the Twenty-First Century" proposal in July last year, which broadly emphasized the importance of nanotechnology, and in March this year, we concluded the study with our "A Future Society Built by Nanotechnology (n-plan21)" proposal, which suggested that nanotechnology must be promoted under a national strategy.

Fortunately, the fiscal 2001 budget enables Japan to start strengthening involvements in nanotechnology, including the Ministry of Economy, Trade and Industry's launching of two programs, Next-Generation Semiconductor Technology Development and Material Nanotechnology, and the Ministry of Education, Culture, Sports, Science and Technology's involvement in preparing a nanotechnology research facility. Furthermore, the Basic Plan for Science and Technology, which sets the fundamental direction for science and technology policies over the next five years, stated that the field of nanotechnology and materials was important. Japan is pursuing activities that must be carried out to further promote nanotechnology, including laying down strategies for promoting nanotechnology at the Council for Science and Technology (CST), which saw its functions strengthened by the recent reorganization of Japanese government and ministries.

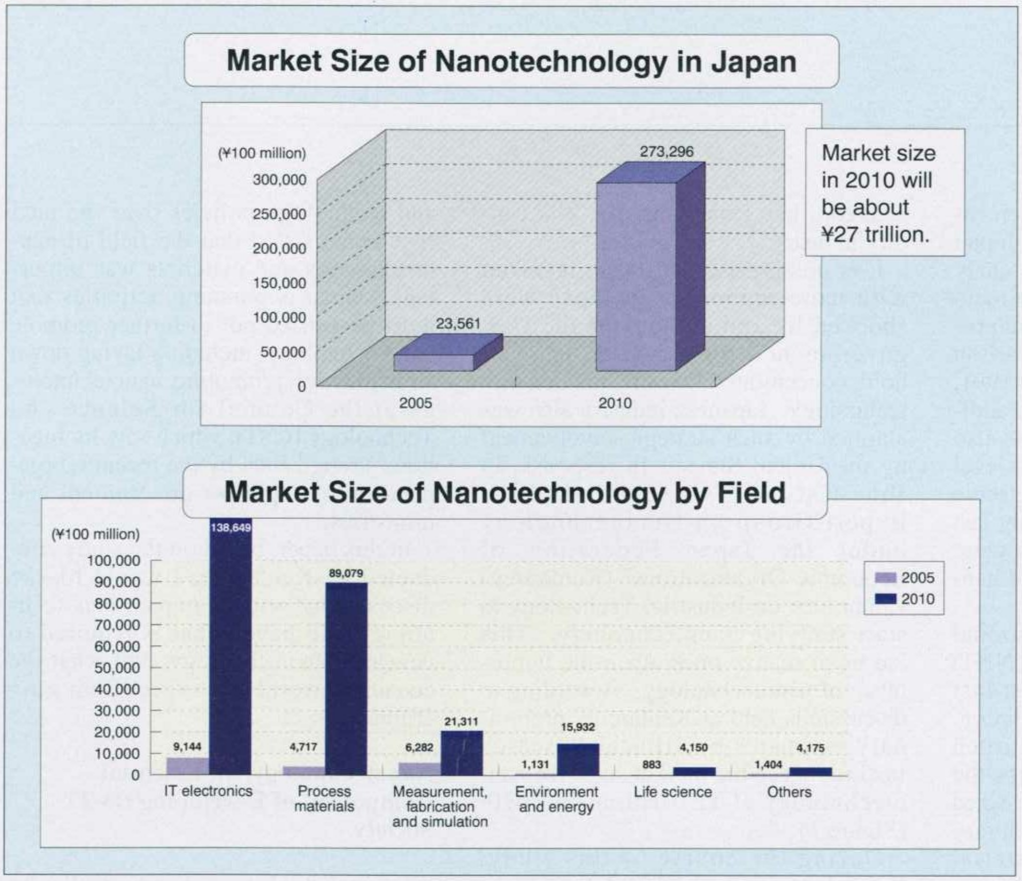
In this paper, based on the study conducted by Keidanren, I would like to discuss what sort of impact nanotechnology will have, what is required to develop nanotechnology, and what the economic world can expect from government.

Nanotechnology, an Essential Component of Developing the IT Society

In its "e-Japan Strategy," the Japanese government revealed that it aims to become the world's leading-edge information technology (IT) nation within five years, and the first application of nanotechnology is expected to be in the IT field. Building a super high-speed network infrastructure and enabling the high-speed processing of vast amounts of information including video for mobile or other applications requires that the processing speed of electronic devices be dramatically accelerated while at the same time greatly decreasing their power consumption. Nanotechnology holds the key to developing such advanced devices.

Some semiconductors – electronic devices that process information – on the market today have already technologically reached the nano level with 180-nm (nanometer) design rules and 3-nm thick gate oxide film. As the refinement of semiconductor manufac-

Figure 1



Note: 1. Based on preliminary calculations by the Hitachi Research Institute (HRI).
2. The life science field is limited to the narrow area where there is an integration of nanotechnology and biotechnology. It excludes what is known as biotechnology, which includes genome drugs and DNA chips.

turing techniques progresses, by about 2003, 100-nm design rules and 1-nm thick gate oxide film will be required. It is said that today's technology would face the limit to catch up with this refinement. Developing faster devices that consume less power will necessitate transcending this limit with nanotechnology.

Eleven Japanese semiconductor companies have launched the Asuka Project to establish a practical fabrication and design technology for a system-on-a-chip (SoC), which mounts memory, logic and other elements on a single chip at the 100 to 70-nm generation. The Japanese government has launched a project, known as the Fundamental Research and Development of Next-Generation Semiconductor Materials and Processes, to develop the fundamental technology for semiconductor processes from the 70-nm generation and on, an area for which the technical outlook is still unclear.

However, semiconductors are not the only form of nanotechnology required to create an affluent IT society. The vast amounts of information that will be produced can only be utilized if there is enough storage space to handle it. And we must not forget the devices for transmitting and receiving such information.

Magnetic disks for storing information represent a data bit by the direction of magnetization. The size of a single bit is around 640x50 nm today. In terms of storage density, that is about 20 gigabits (giga: 10^9 or 1 billion) per square inch. The amount of information that needs to be stored will continue to increase, and estimates hold that by 2010, storage density will reach about 1 terabit (tera: 10^{12} or 1 trillion) per square inch, and the size of a bit will decrease to around 40x20 nm. At that point, the signal detected by the magnetic head becomes extremely weak, and even the magnetization recorded becomes unstable. This necessitates new approaches such as developing heads with new structures that have extremely high reproduction sensitivity and disk material with very high magnetization in the vertical direction, both of which are based on nano order thin film technology.

In addition, enabling data transmission/reception over the Internet at home using light at super high speeds requires that the transmitter/receiver device be reduced from laptop PC-size to about the size of a card. This demands that devices such as wave separation/merge and wavelength converters be reduced to chip-level size, but this too requires nanotechnology. For example, using photonic crystals wherein nanometer-level material is arranged in a very organized structure to develop two-dimensional or even three-dimensional photonic waveguide devices instead of the conventional one-dimensional devices will make possible the manufacture of miniature transmitter/ receivers at a low price.

In the IT field, other devices in which the utilization of nanotechnology is expected include near-field optical memory – the next generation optical storage – and compound semiconductors for the wireless transmission of broadband.

What we require is information itself. Limiting as much as possible the number of devices that come between people and information will eliminate the wasting of resources and energy and enable the exchange of information at higher speeds. Nanotechnology is what will make this possible. To help realize an IT society through nanotechnology, we must aggressively promote its research and development (R&D) in the IT field through collaboration between industry, government and academia.

Nanotechnology's Expected Applications in Environmental and Biotechnology Fields

Nanotechnology holds the potential for major breakthroughs not only in the IT field, but in the environmental and the biotechnology fields as well.

One example is a micro total analysis system (μTAS) that performs measurement, detection, analysis, diagnosis and other tasks as a whole on a single super-small chip. Applications for μTAS include the use of cells to evaluate with high precision the safety of extremely small quantities of chemicals and the effects of pharmaceuticals. Such systems are expected to help improve the health of the Japanese people and may even be applied to environmental and chemical fields as microreactors.

The ability to artificially produce enzymes and antibodies based on the stereostructure information of proteins is expected to find applications in processing substances that are difficult to break down and chemical industry processes that use less energy. This will require the development of technology for analyzing a spatial-temporal network system by observing the dynamics of individual protein molecules.

Furthermore, catalysts that facilitate chemical reactions easily separate, and it is thought to be difficult for them to maintain their activity, but by extracting them from within a support as a nano-level cluster, they become difficult to separate and can be used effectively. This technology would allow the breakdown of methane and the highly efficient extraction of hydrogen, and applications are also expected for the energy field.

Other developments are also expected such as artificial photosynthesis that efficiently produces energy based on the photosynthetic mechanism of plants and recyclable materials that are made of polymers with noncovalent bonds and place little burden on the environment. The environment and biotechnology are fields in which Japan's nanotechnology involvement is still inadequate. The first step must be to widen the support base for fundamental research by having researchers in environment and biotechnology fields exchange information and ideas with those in the nanotechnology field.

Nanotechnology Materials to Support Technological Innovation in the IT, Biotechnology, and Environment Fields

Materials technologies will support technological innovation in a wide range of fields, including IT, biotechnology and the environment, but it will also be nanotechnology that derives the diverse functionality of such materials.

One form of nanotechnology in the materials field is carbon nanotubes, which were discovered by Dr. Iijima Sumio, Research Fellow at NEC Corp. This paper will not provide an in-depth discussion of carbon nanotubes since one of Japan's top researchers, Dr. Yumura Motoo of the National Institute of Advanced Industrial Science and Technology (AIST), has already covered them in another paper. Suffice it to say that carbon nanotubes have epoch-making properties, hold immense potential in a variety of fields, and are currently the material that best represents the field of nanotechnology.

Developing nanoparticle material – particles with diameters of several nm – is expected to dramatically increase properties and functionality. For example, semiconducting nanoparticles with a diameter of around several nanometers offer a sharp emission spectrum over a long period of time and enable the control of color by particle diameter. By combining nanoparticles with proteins, applications to biosensors that use color to identify molecules that bind with proteins are expected.

In addition to nanoparticles, there are a wide range of other applications for nanotechnology in the materials field including nanofilm that is only several nanometers thick and nanocomposites that separate different substances within material at the nano level. The industrial world is also getting involved in many different ways.

Nanotechnology plays an important role not only in functional materials, but also in structural materials as well. Structural materials have the potential to lose strength due to the expansion of small internal defects when external forces are applied. Nanotechnology, which can decrease the size of crystal grains within materials, is the solution. The National Institute for Materials Science (NIMS) was the first in the world to succeed in creating a steel bar two times stronger than normal by reducing the size of the crystal grains in iron to around 500 nm.

The development of structural materials with increased strength by decreasing crystal grain size is not limited to metals. There are also applications for other inorganic materials such as ceramics. This field also holds major possibilities for polymers and organic materials as well as structural materials for such things as automobile bumpers.

According to the Japanese government's comparison of Japanese R&D standards with those in the United States and Europe, Japan has a higher standard for substances and materials than either of the other two areas. With applying this strength, the government must help develop the nation's materials industry by balancing R&D that is clearly aware of its ultimate goals, whether it be IT, biotechnology, or the environment, with R&D that cuts across all types of material removing the barriers between metal, inorganic and organic materials.

Table 1: Fields Demanding Concentrated Investment

1. Flagship Projects

- R&D focused on practical application and industrialization in the next 5 to 10 years
- Network-type Center of Excellence (COE) operation

◆ *IT: Developing Low-Power, High-Performance Technology for Building a Ubiquitous Network Society**

1) Next-generation semiconductor technology
- Transcending design rule limits in semiconductor development
  - Nano-level semiconductor manufacturing/evaluation system
  - New wiring technology
  - Devices with new materials and structures
- Asuka Project: From 100 nm
  MIRAI Project: From 70 nm

2) Terabit-level information storage technology
- Terabit/inch^2 storage density (2010)
  - New materials for storage media and heads • Precision actuators
  - Magnetic heads with new structures • Near-field optical memory

3) Network Devices
- Optical: Petabit/second, Wireless: 10 gigabit/second (2010)
  - Photonic waveguide devices • Super broadband electronic devices

2. Future Projects

- Targeted R&D revolving around developing innovative basic technology
- Network-type COE operation
- Well-timed practical application (including nurturing venture businesses)

1) Nano processes and materials
- Creating innovate functionality through the control of extremely minute structures (nanocrystals, nanofilm, nanoparticles and nanotubes) across many fields
  - Structural materials that are extremely light yet very strong
  - Long-lasting materials • Materials that support energy shifts
  - Electronic materials with new functionality

2) Biological nanosystems
- Creation of innovative diagnostic systems by fusing biotechnology with nanotechnology
  - μTAS • Measurement of single molecules

3) Nanodevices
- Development of new devices for the "generation after next"
  - Photon control devices • Single-electron control elements
  - Spin electronics • Superconducting devices
  - Organic flexible devices

4) Nano-measurement
- Implementation of the precision measurement required for nano-level fabrication and control
  - Increased performance for electron beam/optical measurement
  - Increased performance for probes measurement
  - Nanometer x-ray measurement

5) Nanofabrication
- Implementation of mass-production nanofabrication technology
  - Top-down ultimate fabrication technology
  - Bottom-up technology including self-assembly
  - Integration of top-down and bottom-up technology

6) Nanosimulation
- Development of simulation technology in the nanotechnology field
  - Device design, Computer Aided Design (CAD)
  - Manufacturing equipment simulation

3. Fundamental Research

- Emphasis on researcher creativity
- Clustering of research

1) Search for physical properties of nanostructures and elucidation of their functionality
- Structure and function of artificial lattices, quantum dots, single atoms/molecules, genomes and proteins
- Fundamental technology for intelligent computer systems (quantum computers, atomic/molecular computers and biocomputers)
- Fundamental technology for resource recycling and minimum energy systems • Self-organization

2) Measurement of physical properties
- Precision measurement of electronic state, magnetic state, organization, structure and composition
- Temporal resolution measurement and extremely quiet environment
- Development of new probes

3) Theoretical calculation and analysis

Note:* In the Ubiquitous Network Society, the formation of a high-level information network infrastructure is achieved, and everyone can use network information terminals everywhere.

Measurement, Fabrication and Simulation Technology: Foundations of Nanotechnology

Measurement, fabrication and simulation technology, which are the foundations of nanotechnology, hold a crucial key for developing nanotechnology. It is possible to capture surface topography as an image by placing a superfine metallic needle near the surface of an atom, measuring the infinitesimal tunnel current that flows between them, and then raising and lowering the needle so that the current remains at a fixed value. This is known as scanning tunneling microscopy (STM), and it has contributed to the development of nanotechnology through the creation of a variety of scanning probe microscopy (SPM) techniques, that place a probe near the measurement subject. One such technique is atomic force microscopy (AFM), which enables the measurement of substances that do not conduct electricity very well and targets the forces at work between atoms.

Measurement by beam techniques such as electron beams and X-rays is also crucial for nanotechnology. Measuring the dimensions of minute circuit patterns on semiconductors – semiconductor gate length – requires 1/70 precision. Scanning electron microscopes are mainly used on semiconductor manufacturing lines, but current electron sources have reached a resolution barrier at around 2 nm, and thus cannot meet the needs when circuit patterns reach the 100-nm level. Supporting successive generations of semiconductor production demands scanning electron microscopes that offer an electron source with an extremely narrow energy distribution that can deliver a resolution finer than 1 nm.

How to manufacture, as well as measure, in the nano world are the major issues to be solved. Nano-fabrication consists of the so-called top-down technique that attempts to achieve smaller sizes from larger ones such as semiconductor manufacturing as well as the bottom-up technique, a totally new concept of assembling substances at the atomic or molecular level. One expectation for the bottom-up fabrication technique is self-organization, in which nano-scale structures grow spontaneously under certain conditions.

For example, growing germanium crystals on a silicon substrate results in a structure in which isolated dots are arranged in a relatively regular fashion rather than a uniform layer. The size of each dot is more than 20 nm, and they are known as quantum dots due to the prominent quantum effect(1) that appears. Expected applications for this include semiconductor lasers.

The synthesis of nanotubes and conductive polymer as well as formation processes for proteins and cellular structures are other applications for self-organization. The potential to revolutionize the manufacturing system in the next 10 to 20 years lies in elucidating the mechanism of self-organization so that we can use it to form the nanostructures we desire.

Another basic form of nanotechnology is nanosimulation. To dramatically boost the efficiency of R&D, we must perform nano-level simulations on computers instead of actually conducting tests in a lab. Nanosimulation will enable us to identify R&D targets from the useful results we obtain.

Although we already have classic simulation that targets the macroscopic region and simulation that targets the molecular and atomic levels, there is not yet any simulation technique that combines the two at the nano-level. Nanosimulation technology must be established to develop a nanosimulator for the practical implementation of detailed analysis of semiconductor surfaces and other tests.

Measurement, fabrication and simulation technology provides a common foundation for supporting nanotechnology, and it is a field on which the Japanese government must place great importance.

Promoting Nanotechnology as a National Strategy

As discussed at the beginning of this paper, former President Clinton's NNI was the trigger for Keidanren's interest in studying nanotechnology. Even Europe is getting aggressively involved in nanotechnology. The United States and European nations are adopting aggressive measures to nurture technology that will support 21st-century industry. Although corporations will be the ones who will develop practical applications, universities and public research facilities must play a major role in promoting the research that leads to such applications as well as the fundamental research based on that. The government must determine a strategy for the nation and work hard towards accomplishing it, and it must also prepare the infrastructure for promoting the necessary R&D.

The Japanese mass media often questions whether projects are allocated a budget merely by having the term nano in their name. There is a real danger that precious resources will be squandered if efforts are all show and no substance, or ministries and government offices conduct R&D isolated from one another. The government must promote concentrated R&D that strategically selects and focuses on the necessary fields. Keidanren is also making concrete proposals to the government as presented in Table 1.

It is also important to have a good balance between early-stage fundamental research and research that focuses on practical applications. Japan is conducting fundamental research, but whether it will lead to practical applications is debatable. Promising results obtained through targeted research, primarily at universities and public research facilities that have cutting-edge capabilities, must be quickly brought to the practical application stage and then commercialized by corporations, including venture businesses.

The most important element in the pursuit of nanotechnology research and practical application is the existence of an organization that can grasp and evaluate the overall picture as well as individual projects and that constantly considers and indicates the proper course. Such an organization will grasp and evaluate Japan's involvement in nanotechnology, identify in what fields major nanotechnology investments should be made, and determine what sort of system is best for true integration and coordination between researchers and research facilities.

Fortunately, the recent restructuring of central ministries and government offices has established the CST. The Council is served by a committee and secretariat that study nanotechnology strategy. The CST is establishing clear guidelines for budget allocations and aggressively proceeding with studies for formulating promotion strategies. We strongly hope that the Council is formulating a national strategy so as to prevent the abuses that can occur in vertically organized government, and according to that strategy, promoting nanotechnology in a centralized manner so that it will make major contributions to developing Japan's society and economy. JJTI

Note

1) Quantum Effect: Materials being smaller than a certain size, behaviors explained by quantum theory, such as taking discrete energy levels just as atoms and molecules, become remarkable. The properties and functions specified by quantum theory are known as the "Quantum Effect."

Watanabe Makoto is a Manager at the Science & Technology Group, Environment, Science & Technology Bureau, the Japan Federation of Economic Organizations (Keidanren).