NRI Papers No.37 December 1, 2001

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# Encounters of Atoms, Bits and Genomes

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The National Nanotechnology Initiative (NNI), a top-priority US policy to strengthen its technological competitiveness, enthusiastically advocates nanotechnology research and development. The NNI was instrumental in generating Japan's counteractions to improve the competitive strength of its high-technology manufacturing industries, especially in semiconductors.

Nanotechnology refers to the cluster of emerging technologies that focus on nanoscale ($10^{-9}$ meters) substances and devices that generate new phenomena peculiar to the mingling of atoms, bits and genomes. It provides a common base to support the development of materials, information and biotechnologies—the cutting-edge technologies for the start of 21st century. If Japan's high-tech industries can effectively deal with these technologies, they can be expected to create a number of new business opportunities.

In developing nanotechnology, both the bottom-up and top-down approaches are essential. Under the former, nanostructures are assembled to build macrostructures that can fulfill technological functions, whereas the latter proceeds by employing ultra-miniaturization to move from macrostructures to nanostructures. The essence of nanotechnology can be found in "paradigm shift" models, where the top-down and the bottom-up approaches converge.

Nanotechnology is expected to bring about revolutionary changes not only in technological fields but also in R&D management. In order to realize the development and implementation of nanotechnology, it is necessary to make drastic changes in our way of thinking about R&D—including management systems in public R&D institutions, role sharing and cooperation among governmental, industrial and academic organizations, the handling of intellectual property, and support for starting venture businesses. Japan has advanced in some important areas of nanotechnology and has produced a number of pioneers in the field. We should try to overcome the prevailing economic difficulties by utilizing this potential, and by actively promoting strategies aimed at implementing nanotechnology on the basis of the suitable R&D management systems.

# I Technological Paradigm Shift

The spate of recent news stories related to nanotechnology continues to draw our attention to this new field. Indeed, the term has come to represent a key word that seems to open up the magic world of advanced technology that will support the developments of the 21st century. In Japan's industrial circles, however, most leaders seem to have adopted a wait-and-see attitude, as they expect that the commercialization of nanotechnology will occur only at some distant time in the future.

However, there are some prescient observers who have a growing sense of crisis and argue that nanotechnology "is a basic technology that is likely to have a far-reaching impact on the industries of the 21st century. As aggressive growth in information technology (IT) and biotechnology cannot be sustained without nanotechnology, we should see it as the common basic technology for all industries."[1]

The current enthusiasm relating to nanotechnology stems from National Nanotechnology Initiative adopted by former US president Bill Clinton in 2000. The NNI is an action plan put forward by the Clinton Administration to strengthen the international competitiveness of US industry over the next 10 to 20 years to compete with high-tech manufacturing industries in Japan and other developed countries.

The NNI defines nanotechnology as technologies to configure atoms and molecules on a nanoscale ($10^{-9}$ meters) basis by means of certain design guidelines to realize the intended functions. To achieve this purpose, a completely different concept (the bottom-up approach) that departs from the traditional miniaturization concept (the top-down approach) is required.[2] In sum, nanotechnology has been innovative in adopting the bottom-up approach to overcome the limits that we will necessarily encounter if we continue to pursue the traditional top-down methods that are used in the miniaturization and precision manufacturing of semiconductor memories or magnetic disks.

In actuality, the idea of artificially creating substances and materials themselves as well as their functions under the bottom-up paradigm is increasing its importance for the functional materials supporting next-generation IT, namely in the field of new electronics devices. In other words, in addition to traditional ultra-miniaturization, it is indispensable for the future development of functional materials and devices to adopt a method of assembling atoms and molecules as macro-scale materials in manufacturing new electronics devices.

Such technological applications may be expanded further. For example, the bottom-up approach to assemble nanoscale materials is becoming an effective tool in the field of "post-genome" research efforts, in which work to decipher the human genome has almost been completed in cooperative efforts among the United States, Japan and Europe, and new focuses are now concentrating on proteome, genome based drug development and "personalized" medicine.

Accordingly, nanotechnology should be recognized as a basic technology common to all atoms, bits and genomes (materials, data and genetic engineering) as it may result in the convergence of traditional top-down technology (miniaturization) with the newly developed bottom-up technology.

The development of new properties incorporated in nanoscale structures—as well as functional materials and devices through the bottom-up approach—is now swiftly beginning to take shape and is no longer just a dream of the future. In short, a paradigm shift in advanced technologies through nanotechnology is steadily developing. We must understand that the results of these research efforts can be practically implemented more quickly than previously thought. In fact, many new ventures have been launched in the United States to take on these new business opportunities.

Although there have been a number of pioneers in nanotechnology in Japan, fundamental systems have not yet been implemented to develop their potential into new businesses. Structuring these systems is an important task that Japan must face. It is also important for individual companies to actively develop long-term business strategies that take into account the diversity and general applicability of nanotechnology in pursuing this paradigm shift.

Chapter II of this paper discusses the US nanotechnology strategy represented by the National Nanotechnology Initiative, and corresponding movements in Japan. In Chapter III, the technological features of nanotechnology and the background of its development are analyzed.

Chapter IV will introduce the basic concept in nanotechnology and pioneers who have led the research efforts, with a focus on a number of pioneers in Japan who have not been fully evaluated but who have made significant contributions to diverse applications described in the NNI. Several technical features will also be presented through actual examples.

Chapter V will focus on the potential impact of nanotechnology in various fields by referencing the research results of these pioneers, and will introduce the current status of the bottom-up approach. Chapter VI will propose future tasks to effectively promote nanotechnology development by concentrating on the possible evolution in R&D management strategies. Finally, Chapter VII will make suggestions for private industries on how to deal with nanotechnology issues.

# II The National Nanotechnology Initiative and Japan's Reactions

## 1 Nanotechnology Shock Originating from the United States

### (1) Clinton's speech

On January 21, 2000, less than a year before he left office, US President Bill Clinton made a historic speech at the California Institute of Technology, where a number of prominent scholars (including Professor Richard P. Feynman, who will be introduced later) were working.

"My budget supports a major new National Nanotechnology Initiative worth $500 million," the president said. Among other things, it will focus on "the ability to manipulate matter at the atomic and molecular level. Imagine the possibilities: materials with ten times the strength of steel and only a small fraction of the weight, shrinking all the information housed at the Library of Congress into a device the size of a sugar cube, and detecting cancerous tumors when they are only a few cells in size. Some of our research goals may take 20 or more years to achieve, but that is precisely why there is an important role for the federal government."[2]

Nanotechnology was selected as an important theme to generate pride among people in the United States to become pioneers on the intellectual frontier at the time of the technological conversion at the end of the 20th century.

### (2) Strategy in selecting NNI

Before President Clinton publicly announced the NNI for the first time, detailed debates had continued for four to five years in the industrial, political and academic worlds regarding the establishment of a formal policy to promote nanotechnology as part of the nation's technological and scientific strategy. The White House's National Science and Technology Council set up a Subcommittee on Nanoscience, Engineering and Technology in September of 1998, in which several representatives from each government agency are participating. This subcommittee operates under the auspices of the Technology Committee, which consists of officers with rank of undersecretary.[3]

The subcommittee has worked to refine the NNI draft through research meetings and forums attended by prominent scholars and researchers from academe and industry. As part of this process, international comparative surveys on the level of nanotechnology research conducted during the period between 1996 through 1998 by the International Technology Research Institute at Maryland's Loyola University have played an important role.

### (3) International comparison of nanotechnology research levels

Under this research project, a team headed by Professor Richard W. Siegel of Rensselaer Polytechnic Institute was established with four members from the academic world including Professor Siegel and four members from the industrial sector. These members visited related research organizations in Japan (18 institutions) and Europe (six countries and 16 institutions) to elicit views on nanotechnology developments. The team reported the current status of research activities in these countries and prepared a report entitled "Comparison of Activities in Nanostructure Science and Technology in Europe, Japan, and the United States" (see Table 1). Although the table is based on the subjective evaluations of team members, it does provide a general overview of comparative levels of nanotechnology development activities.

According to this report, the United States is the nation that is strongest in nanostructure manufacturing and assembly, catalyst technologies (surface activate materials), followed by Europe and Japan. The United States and Europe are matched in biotechnology approaches and applications, dispersions and surface coatings, followed by Japan. Japan is the leader in the fields of nanodevices (semiconductors and magnetic or optical devices), consolidated materials (high-strength and low-weight metals, ceramics and high-performance magnets) followed by the United States and Europe.

**Table 1. Comparison of Activities in Nanostructure Science and Technology in Europe, Japan, and the United States**

| Technology | Level | | |
|---|---|---|---|
| | 1 (Highest) | 2 | 3 |
| **Synthesis & Assembly** | US | Europe | Japan |
| **Biological Approaches & Applications** | US, Europe | Japan | |
| **Dispersions and Coatings** | US, Europe | Japan | |
| **High Surface Area Materials** | US | Europe | Japan |
| **Nanodevices** | Japan | Europe | US |
| **Consolidated Materials** | Japan | US, Europe | |

Source: R.W. Siegel, E. Hu, M.C. Roco, WTEC, Loyola University, ed., *Nanostructure Science and Technology: A Worldwide Study*, Interagency Working Group on Nanoscience, Engineering and Technology (IWGN), September 1999.

### (4) Budgets for NNI activities

The US government has proposed an investment of $495 million in nanotechnology development for fiscal 2001 (October 2000 through September 2001). (See Table 2.) A breakdown of this total shows 62.6 percent allocated to basic research and Grand Challenges, with the remaining 31.7 percent allocated to new centers and networks of excellence (COEs) and implementing research infrastructure improvements at existing institutions. It should be noted that universities are becoming the center of nanotechnology research (roughly 70 percent of the budget is earmarked for universities).[2]

Budget allocations by government agencies indicate that the National Science Foundation (NSF) receives the largest share, followed by the Department of Defense and the Department of Energy. Most of these funds are allocated to universities or companies to conduct basic research activities. Conversely, relatively small amounts are allocated to the Department of Commerce and its related agencies, such as the National Institute of Standards and Technology (NIST), which is carrying out various important projects such as the Semiconductor Manufacturing Technology Consortium (SEMATEC) to develop next-generation semiconductors, and R&D in the area of high-performance magnetic disks under the Advanced Technology Development Program (ATP).

The National Institutes of Health (NIH) have also received relatively limited funding, despite the major role of the institutes in conducting biotechnology research in the United States. NIH allocations under the NNI budget ($4.5 million for fiscal 2002) are little more than a drop in the ocean when compared to the total federal budget of $23.1 billion set aside for the NIH.[4]

The larger allocations to universities may indicate the NNI's intention to concentrate funds on long-term basic research in relation to bottom-up technologies, as the NNI recognizes that these developments constitute the core technologies in the advancement of nanotechnology. On the other hand, the smaller allocation to the Department of Commerce does not mean that top-down technologies—such as next-generation semiconductors, information storage devices or biotechnology—are excluded from priority consideration in nanotechnology development. Instead, it represents the belief of the government that these top-down technologies should be primarily carried out by the private sector. The smaller allocations to the NIH mean that redundant expenditures should be avoided, as the NIH are already working on biotech-related research projects.

### (5) Infrastructure improvement and human resource development

In light of the long-term nature of the nanotechnology initiative, the NNI has concentrated on the development of human resources for the next generation and the improvement of infrastructure to support such developments,

**Table 2. Breakdown of US Government R&D Expenditures Related to NNI**

**<By Project>** (Unit: $ Million)

| | Basic Research | Grand Challenges | Centers and Networks of Excellence | Research Infrastructure | Ethical, Legal, and Social Implications and Workforce | Total |
|---|---|---|---|---|---|---|
| **Fiscal 2000** | 87 | 71 | 47 | 50 | 15 | 270 |
| **Fiscal 2001** | 177 | 133 | 77 | 80 | 28 | 495 |

**<By Agency>** (Unit: $ Million)

| | NNI Budget | | | US Government R&D Budget | | |
|---|---|---|---|---|---|---|
| | **Fiscal 2000** | **Fiscal 2001** | **Fiscal 2002** | **Fiscal 2000** | **Fiscal 2001** | **Fiscal 2002** |
| **National Science Foundation** | 97 | 217 (150) | 174 | 3,897 | 4,416 | 4,472 |
| **Department of Defense** | 70 | 110 (110) | 133 | 4,541 | 4,981 | 5,086 |
| **Department of Energy** | 58 | 94 (93) | 97 | 4,353 | 4,910 | 4,682 |
| **NASA** | 5 | 20 (20) | 46 | 6,389 | 6,957 | 7,038 |
| **Department of Commerce** | 8 | 18 (10) | 17.5 | 819 | 809 | 711 |
| **National Institutes of Health** | 32 | 36 (39) | 45 | 17,827 | 20,361 | 23,112 |
| **Total** | 270 | 495 (422) | 518.9 (2) | 83,138 | 90,010 | 95,253 |
| **Basic Research** | | | | 19,421 | 22,018 | 23,352 |
| **Applied Research** | | | | 18,466 | 20,734 | 21,553 |
| **Development** | | | | 40,524 | 42,594 | 45,954 |

Notes: (1) Figures for fiscal 2000 are actual, while those for fiscal 2001 and fiscal 2002 are requested budgets (figures in parenthesis are actual government budgets); (2) the total NNI budget for fiscal 2002 includes $1.4 million for the Department of Justice (most of which relates to research on DNA chips for forensic medicine) and $5 million for the Environmental Agency (mostly for research relating to environmental purification); (3) the total US federal government science & technology budget covers all research expenditures incurred by the government; (4) COE: centers and networks of excellence.
Source: Prepared from National Science and Technology Council, "National Nanotechnology Initiative: The Initiative and Its Implementation Plan," June 2000, "National Nanotechnology Investment in the Fiscal 2002 Budget Request by the President." (http://nano.gov/2002budget.html)

which are essential for the entire project. This requirement is clearly reflected in the goals established for the NNI over the next five years.

Actually, these milestones set the following targets: (1) establishing centers and networks of excellence by 2003 that include ten new research centers equipped with nanoscale measuring and manufacturing facilities; (2) developing physical and chemical 3-D measuring methods by 2004 that are capable of conducting nanoscale performance evaluations, operations, standard systems for devices and atom-based resolution; (3) improving and arranging environments for allowing more than half of the researchers and students nationwide to use COE research facility networks by 2005 to help in building capacity.

With the support of the National Science Foundation, the National Nanofabrication Users Network (NNUN) has already been established to link five universities nationwide, including Stanford University. The objective of this network is to provide the most advanced nanofabrication technologies to researchers and students in all universities, national and public research institutes, and corporate research centers.

## 2 Initiatives Taken by Japan

In response to the initiatives taken by the United States, how has Japan reacted with respect to gaining leadership in this important field?

### (1) Reactions to the National Nanotechnology Initiative

Under the first Science and Technology Basic Plan, Japan had invested a total of ¥17 trillion in R&D activities during the five years from fiscal 1996 through 2000. Thanks to the considerable budget allocations to nanotechnology-related fields, a number of pioneering results were successfully achieved before the announcement of the NNI. As these research and development efforts were essentially being carried out on an individual basis and were not part of a comprehensive plan, it therefore appears that the core recognition that sees nanotechnology as a fundamental technology common to a wide variety of advanced technologies—and one that will lead to a paradigm shift in R&D activities—has not yet taken form.

Under these circumstances, it was the industrial world in Japan—especially the Japan Federation of Economic Organizations (Keidanren)—that most quickly reacted to the NNI announcement. With a keen sense of impending crisis, Keidanren has made a number of strong appeals to the government to promote nanotechnology development. These concerns can best be summarized by the statement issued by Chairman Tsutomu Kanai of Hitachi Ltd.: “Japan’s R&D [in the field of nanotechnology defined by the NNI] is among the top levels in the world. We believe that this current position can be maintained. We must not commit the same error as we did for biotechnology.”[5]

### (2) Approaches by the Council for Science and Technology Policy (March 2000 through April 2001)

This section focuses on Japan’s major moves towards nanotechnology between March 2000 and April 2001 by examining the activities of Keidanren and the industrial world and the budgetary requests of government ministries, as outlined in Table 3. It was during this period that the establishment of the next Science and Technology Basic Plan was referred to the Council for Science and Technology Policy.

On May 16, 2000, Keidanren issued its “Proposals for the Realization of a New Virtuous Cycle of Demand and Supply: Creation of Leading Industries and Fields for the 21st Century,” in which nanotechnology was cited as a new frontier technology to be strengthened. In the following month, a nanotechnology subcommittee (led by Hitachi R&D Director Michiharu Nakamura) was newly established under the Committee on Industrial Technology (headed by Hitachi Chairman Tsutomu Kanai) to start efforts to develop a consensus among all industries.[6]

In its calls for government action, Keidanren stressed its intention to make strong appeals to the Conference on Industrial Competitiveness and the Council for Science and Technology Policy on the grounds that the promotion of nanotechnology research is essential in enhancing Japan’s industrial competitiveness, particularly in information technology.[7] Keidanren also issued various public statements, such as “Expectations for the New Administration” on July 6, 2000 and “Nanotechnology Opens the Road to the 21st Century—Keidanren’s Concept for Nanotechnology” on July 18, 2000, in which the federation proposed that the government should promote nanotechnology development as a national project.

The points pursued by Keidanren in these statements include the following: (1) nanotechnology is a fundamental technology that controls the progress of the IT revolution; (2) it is also an essential technology that exerts a considerable impact on next-generation industry as well as on the society of the future; (3) it is important to establish long-term policies with a focus on basic and infrastructural research and development efforts, as well as to take appropriate measures for the timely commercialization of the results; and (4) it is essential for related government organizations to take united approaches in cooperation with industry and academe under a national strategy.

In line with these moves, ministries and agencies have incorporated new nanotechnology policy measures in their estimated budget requests for fiscal 2001. For example, the Ministry of Education, Culture, Sport, Science and Technology (MEXT) has requested ¥14.9 billion (¥12.3 billion in fiscal 2000) to strengthen the promotion of research in nanosubstances and nanomaterials,

**Table 3. Moves Towards Nanotechnology Development by the Japanese Government and Industry**

| **Moves by Government (including the Council for Science and Technology Policy)** | |
|---|---|
| Year 2000<br>March 24 | **(CSTP)**<br>Requesting advice on the next-term science and technology basic plan. |
| June 29 | **(CSTP)**<br>Adopted "Guidelines on Priorities for the Promotion of Science and Technology in Fiscal 2001" that added the "substances and materials area." |
| Aug. 31 | **(MEXT, METI)**<br>Submitted estimated budget requests for fiscal 2001. |
| Sep. 14 | **(CSTP)**<br>Set up a "Discussion Group on the Strategic Promotion of Nanotechnology" and started to determine objectives and priority areas. |
| Dec. 14 | **(CSTP)**<br>Announced "Report of the Discussion Group on the Strategic Promotion of Nanotechnology." |
| Dec. 26 | **(CSTP)**<br>Responded to the request for advice on the next-term science and technology basic plan; designated the field of nanotechnology and materials as priority areas. |
| Year 2001<br>April 19 | **(CSTP)**<br>Established the Nanotechnology and Materials Project at the Expert Panel for the Promotion of Prioritized Areas. |

| **Moves by Industry (including Keidanren)** | |
|---|---|
| Year 2000<br>May 16 | **(Keidanren)**<br>Announced "Proposals for the Realization of a New Virtuous Cycle of Demand and Supply" in which nanotechnology was cited as a new frontier technology to be strengthened. |
| End of June | **(Keidanren)**<br>Set up Nanotechnology Expert Panel under the Industrial Technology Committee. |
| July 6 | **(Keidanren)**<br>Announced "Expectations for the New Administration" and proposed nanotechnology promotion as a measure to increase Japan's strength in industrial technologies. |
| July 18 | **(Keidanren)**<br>Announced "Nanotechnology Opens the Road to the 21st Century: Keidanren's Concept." |
| Sep. 29 | **(EIAJ)**<br>Announced "Joint Development Project in Advanced Semiconductor Technology." |
| Year 2001<br>March 27 | **(Keidanren)**<br>Announced "Future Society to Be Created by Nanotechnology" (n-Plan 21). |

Notes: CSTP = Council for Science and Technology Policy; MEXT = Ministry of Education, Culture, Sport, Science and Technology; METI = Ministry of Economy, Trade and Industry; Keidanren = Japan Federation of Economic Organizations; EIAJ = Electronics Industries Association of Japan.
Source: Nomura Research Institute.

including new policy measures on the promotion of nanotechnology to lead advanced science and technology (¥3.25 billion).[8]

At the same time, the Ministry of Economy, Trade and Industry (METI) has asked for ¥5 billion for a materials nanotechnology program that includes eight projects involving precision polymer technology, nanoglass technology, nanometals technology, nanoparticle synthesis and functioning technology, nanocoating technology, nanofunction synthesis technology, nanomeasuring technology and the structuring of materials engineering knowledge.[9]

METI has also requested ¥6 billion for a project to develop technology in semiconductor device processing (MIRAI Project), with a target of achieving a minimum line width of 70 nanometers for integrated circuits in fiscal 2004 and 50 nanometers in fiscal 2007. In the private sector, a joint development project in advanced semiconductor technology (Asuka Project) was launched on September 26, 2000.[10] This is an epoch-making undertaking supported by eleven semiconductor manufacturers with an R&D investment of ¥76 billion over five years and a target of realizing design and device processing technologies at the level of 70–100 nanometers. Thus, a joint development system uniting the public and private sectors was established for R&D efforts in the field of top-down nanotechnology, specifically for semiconductor ultra-miniaturization technologies.

Keidanren's "Future Society to Be Created by Nanotechnology" (n-Plan 21) announced on March 27, 2001 is a compilation of public and private sector efforts in Japan. This statement proposes the following priorities in nanotechnology development: (1) flagship projects targeting commercialization within five to ten years (next-generation semiconductor technologies, terabit information storage technologies, and network devices); (2) undertaking projects focusing on revolutionary basic technologies (material processing, biotech-nanosystems, nanodevices, nanomeasuring, nanopro-cessing, and nanoscale-simulation phenomena); and (3) basic research (research on physical properties and functional analysis, measuring and theoretical calculation analysis in nanostructures).[11]

Currently, discussions are under way in the Expert Panel of the Nanotechnology and Materials Project (chief researcher: Hideki Shirakawa, recipient of the 2000 Nobel Prize in Chemistry) under the Council for Science and Technology Policy. Their major targets are to define the prioritized areas and to find a way in which the top-down and the bottom-up approaches can be converged.[12] These efforts will be reflected in scientific and technological priority measures in the budget requests for fiscal 2002.

# III Why Nanotechnology Now?

## 1 Nano- Means One-Billionth

Although the term has been used up to now without a detailed explanation, let's go back to a definition of nanotechnology. Nano- is a prefix used in unit systems that means one-billionth of something. One-thousandth of a meter is a millimeter (mm), and one-thousandth of a millimeter is a micrometer ($\mu$). A nanometer (n) is one-thousandth of a micrometer. As nano- is usually used as a prefix to the word meter (which is a unit of length), nanotechnology should more properly be called nanometer (nm) technology if one prefers a strict expression.

There are several examples. The thickness of a hair is normally 50 microns ($\mu$m), the size of a red or white blood cell is 2 to 5 microns, and the size of a mitochondrion and a virus is 100 and 10 nanometers (nms), respectively. The radius of the double spiral in DNA is 2 nms, and the length of the combined oxygen and hydrogen molecule (water) is 0.1 nm. Generally speaking, nanotechnology covers objects that fall into the range of 0.1 to 100 nms. Accordingly, it includes sizes from that of water molecules to mitochondria among the above examples.

On the other hand, as the wavelength of visible light ranges from 400 to 700 nms, it exceeds the range of nanotechnology. And as light cannot resolve sizes smaller than its wavelength, structures with a scale smaller than 100 nanometers cannot be directly observed by the use of visible light. We need light that ranges from vacuum ultraviolet light (100 nanometers) through soft X-rays (0.1 nanometer) to measure nanoscale structures optically.

## 2 Background Behind the Birth of Nanotechnology

As described earlier, the National Nanotechnology Initiative defines nanotechnology as technologies to configure atoms and molecules on a nanoscale basis by means of certain design guidelines to realize the intended functions. There are three background factors behind the emergence of nanotechnology.

The first is the development of analyzing techniques that can be used to directly observe nanoscale structures. Because nanoscale structures cannot be observed by the use of optical tools, the scanning probe microscope (SPM) and transmission electron microscope (TEM) were developed as alternative techniques to directly observe and measure nanostructures such as crystal structures and DNA. The development of these new tools has resulted in the discovery of new nanostructures, as well as fullerenes that will be detailed later. As a result, unique functions based on nanostructures have been discovered, leading to expectations of applying such functions to materials, devices, protein synthesis and the creation of new genome-based drugs.

The second factor relates to the rapid development of miniaturization processing techniques for semiconductors. Because of the progress in this area, inherent technological difficulties were foreseen in the event that the size of unit devices would begin to move into the nanoscale range.

More specifically, when the miniaturization of integrated circuits for DRAM (semiconductor memory) chips advances to the extent that the size of a transistor (a unit device composing the chips) approaches the nanoscale range, a number of technological difficulties are expected to arise. In order to resolve these difficulties, it is necessary to develop a new unit device (e.g., a single electron transistor) in nanoscale and to assemble groups of such transistors to meet specific needs. It is generally recognized that the assemblage of such nanoscale devices would require a drastic shift from the traditional top-down approach to a completely new approach.

In the National Nanotechnology Initiative, such a completely new approach is called the bottom-up approach. Thus the third factor contributing to the emergence of nanotechnology is the recognition of the effectiveness and innovativeness of the bottom-up approach.

In the nanoscale world, new functions are expected to emerge that cannot be seen in the macrostructure world. The bottom-up approach can build up these nanoscale structures into macroscale structures, integrating functions of unit devices. This methodology is commonly effective in various fields of advanced technology, including biotechnology, materials, and information-related devices. This innovative feature of the bottom-up methodology is regarded as the third factor for the birth of nanotechnology—along with the development of nanoscale measuring techniques and the technological difficulties foreseen in further miniaturizing semiconductors devices.

# IV Pioneers in Nanotechnology Development

## 1 Concepts Discovered by Pioneers

### (1) Suggestions by Feynman

The National Nanotechnology Initiative noted that it was Richard Feynman of the California Institute of Technology (recipient of the 1965 Nobel Prize in physics along with Shintaro Tomonaga and Julian Schwinger) who first suggested the concept of nanotechnology to the world. Feynman delivered his now famous lecture, "There is Plenty of Room at the Bottom" in 1959 at the California Institute of Technology, in which he offered the vision of exciting new discoveries if one could fabricate materials and devices at the atomic and molecular scale.[13]

Feynman pointed out in this lecture that the frontiers of knowledge and technology at which people should be aiming could be found not only in physics, including the theory of elementary particles or the theory of gravitation, but also in nanosized fields where all phenomena are believed to be understood in theoretical terms.

He also argued that judging by their potential impact and practical usefulness to society in general, nanosized fields assume a greater importance than other areas as a subject of research. As specific examples, he cited a high-density memory in which only one thousand atoms can represent a bit, and ultrahigh-speed computers utilizing the functions of nanostructures. Most of these examples are cited in the NNI, indicating Feynman's foresight in this regard.

### (2) Molecule engines by Drexler

Dr. Eric Drexler of the Foresight Institute proposed molecule nanotechnology in his 1986 book *Engines of Creation: The Coming Era of Nanotechnology*.[14] He developed the idea of a molecule machine, which is a robot synthesizing protein at the atomic level, on the basis of existing knowledge in biotechnology—starting from DNA (deoxyribonucleic acid), RNA (ribonucleic acid), to ribosomes (assuming the role of catalytic reactions in cells for protein synthesis). While some say that his concepts have exerted significant influence on research into MEMS (micro-electro-mechanical systems) and micromachines, his ideas were so novel that they were often not taken seriously and sometimes criticized as "crazy." Accordingly, they did not reach the point of securing the extensive support that is now enjoyed by nanotechnology.

## 2 Pioneers in Nanotechnology

Even today—some half a century after Feynman's famous lecture—there remain a number of undiscovered new formations and new phenomena resulting from the nanoscale structures.

### (1) Osawa's prediction of fullerenes

A simple example of such new structures is seen in the fullerene C60 soccer-ball-shaped molecules. In the past, carbon molecules were believed to have three basic shapes: diamond-type, graphite-type and amorphous-type. In September 1984, however, Richard E. Smalley and Robert F. Curl of Rice University, and Harold W. Kroto of the University of Sussex in England discovered the existence of the fourth type of carbon molecule. These soccer-ball-shaped molecules, created by linking together 60 carbon atoms, represented a closed-shell structure comprising twelve equilateral pentagons and twenty equilateral hexagons. Smalley and two other researchers named such structures fullerenes (a generic term for carbon-family compounds consisting of such a closed-shell structure, including C60). The three scholars were awarded the Nobel Prize in chemistry in 1996.

It should be noted that a Japanese scholar had predicted the existence of fullerenes. In 1971, Toyohashi University of Technology Professor Eiji Ohashi (then an assistant researcher at Kyoto University) predicted the existence of a soccer-ball-shaped C60 molecule in his book *Kagakudojin (Properties of Aromatics)*, coauthored with Kinki University Professor Zenichi Yoshida. Ohashi later told Smalley that his book had generated almost no reaction partly because it was written in Japanese.[15]

In response, Smalley noted that the new type of carbon molecules attracted considerable attention because they were named fullerenes after R. Buckminster Fuller, who was well known for his design of the geodesic dome structure called "buckyballs.[16] He and his group also insisted on calling the carbon nanotube to be described later as a "Bucky tube." We often see international competition in the world of scientists with respect to naming a new discovery (i.e., becoming the godfather of discovered materials or phenomena), as this conveys a special cachet in terms of the originality of the discovery.

### (2) Discovery of fullerenes

Let us return to the topic of the discovery of fullerenes. At the time, Smalley and Curl had been searching for clusters with a specific molecular weight through a process of bombarding silicon and germanium with laser beams and analyzing the evaporating clusters (groups of atoms) by mass spectroscopy. Kroto was working on interstellar matter (matter existing in the near-vacuum of outer space) that attracted his attention, and asked Smalley to initiate a joint research program to artificially create a carbon cluster with a large mass similar to those he had found in interstellar matter. About a year later, Kroto received a favorable response to his request.

As preparation for the joint research efforts proposed by Kroto, preliminary experiments using graphite plates were implemented on carbon clusters. At the time, a post-graduate researcher who was operating the mass spectroscope during these preliminary experiments noticed the existence of a strong peak in response to carbon-60.[15] However, Kroto and his group failed to recognize this great discovery, as they were concentrating on clusters having a very small mass.

A similar missed opportunity had occurred at an Exxon research laboratory as well. Sumio Iijima of NEC (also a professor at Meijo University) who later discovered the carbon nanotube had observed an "onion-like globe" under an electron microscope in 1980 and had written a paper in which he noted that "twelve pentagons in addition to a hexagon are necessary."[17] In short, Iijima had actually observed the new carbon structure C60, but failed to recognize the importance of his discovery, while Smalley and his colleagues noticed the existence of C60 and gained the great honor of being credited with the discovery.

This episode tells us that even if there are some new discoveries in measured data, it is often very difficult to recognize them. Preconceptions must be eliminated first through the flow of new knowledge in order to make new discoveries. This is a lesson provided by the story behind the discovery of the fullerene—a truly novel substance.

### (3) Iijima's discovery of the carbon nanotube

The discovery of C60 gave a considerable stimulus to research activities in carbon chemistry. New discoveries were successively reported, such as a molecule with an atomic weight of 70 (C70) and those of even greater atomic weights. Finally in 1991, Iijima discovered the carbon nanotube, the current topic of interest in this field.

The details surrounding this discovery also bespeak of how experiments and observations that are normally believed to be objective can still be restricted under existing paradigms. Let us follow the process of the discovery based on Iijima's lecture entitled "Carbon Nanotubes—The Tiniest Man-Made Tubes," which was presented on May 9, 1995 under the Friday Evening Discourses program at Great Britain's Royal Institution in London.[17]

Following the discovery of the fullerene, scientists throughout the world desperately started looking for new carbon molecules through arc discharge techniques, but failed to find any new molecules other than fullerenes, as most of them concentrated their discovery efforts on soot-related materials. Iijima, on the other hand, analyzed carbon clusters deposited on the carbon electrode (negative electrode) of the arc discharge and found a number of needle crystals as well as fullerenes under high-resolution electron microscopes. This was the moment of the discovery of carbon nanotubes (1991).

He further analyzed the structure of the needle crystals by electron diffraction and found a multiple-layer structure of carbon nanotubes consisting of tubes in which smaller diameter tubes were nesting. In 1993 he also succeeded in synthesizing single-layer nanotubes with a diameter of one nanometer by adding metal to the positive carbon electrode. As the electrical conductivity of carbon nanotubes can be modified by changing their diameters or by adding impurities, nanotubes can demonstrate diverse properties as a metal, semiconductor or superconductor, leading to expectations for a wide variety of applications.

Following the finding of carbon nanotubes, a number of new discoveries and inventions based on this material have been introduced throughout the world. These include the development of synthesizing technologies for large-volume production of carbon nanotubes by the former National Institute of Materials and Chemical Research (currently the National Institute of Advanced Industrial Science and Technology (AIST) of Japan's Ministry of Economy, Trade and Industry) and Showa Denko; the start of mass production of cup-type layered-carbon nanotubes by Gunze Sangyo (Japan) ; the development of field-emitter-type ultra-bright light-source tubes by Ise Electronics; the development of the world's first transistor by IBM; and the realization of superconductivity at −220°C by the use of a field-effect transistor structure by Bell Laboratories (US).

### (4) The invention of the scanning probe microscope (SPM)

An epoch-making event in the efforts to observe nanostructures was the invention of the scanning tunnel microscope (STM) in 1981 by Drs. Gerd Binnig and Heinrich Rohrer of IBM's Zurich Research Laboratory. This microscope, which enables researchers to directly "see" the images of atoms, earned the two researchers (along with Dr. Ernst Rusaka of the Max-Planck Fritz-Haber Institute, who made substantial contributions towards the development of the high-resolution electron microscope) the Nobel Prize in physics in 1986.

The STM uses a pointed probe that comes very close (less than one nanometer) to the surface of the sample. When an electrical voltage is applied to the probe, the current passes from the probe to the sample surface as a result of the tunnel effect. Changes in the intensity of the electric current can be measured while scanning the probe on the sample surface, and the changing values can be processed into images. The process makes it possible to obtain images with a resolution power of one atom. Furthermore, Dr. Binnig and his group developed the AFM (atomic force microscope) by expanding the principle of the STM and using the atomic force between the probe and the sample surface in place of the tunnel current.

Newly developed devices such as the STM, AFM and SNOM (scanning near-field optical microscope) are collectively called SPMs (scanning probe microscopes) and have opened the way to a new world of atomic image observation. The emergence of these SPMs is a turning point in the world of nanotechnology research that made it possible for the human eye to directly observe atoms and molecules for the first time. These microscopes are now essential research tools in nanotechnology.

### (5) Quantum mirage

The tunnel current and atomic force used in scanning probe microscopes have enough energy to manipulate atoms. Accordingly, SPMs are now being used not only for observing atomic images but also as a tool for maneuvering individual atoms.

It was Dr. Donald M. Eigler, an IBM research fellow, who carried out an experiment that fascinated scientists and researchers around the world by the use of atomic maneuvering techniques. With two other researchers, Eigler used the scanning tunneling microscope (STM) to position 35 individual xenon atoms on the surface of a single crystal of low-temperature nickel to spell out the letters I-B-M. These were the smallest letters ever written by a human being.

Eigler further tried to move several dozen cobalt atoms on a copper surface into an ellipse-shaped ring (major axis of 20 nanometers and minor axis of 10 nanometers), and found that the electrons in the nanoscale range waved with an intensity just like that on the surface of water—directly demonstrating that they produce a wave pattern as predicted by quantum mechanics.

These results were announced in 1993, and significant progress has been made in subsequent research. In one experiment, when energy was supplied to an atom of magnetic cobalt placed at one focus of an ellipse made with cobalt atoms, an electron wave was generated with the cobalt atom as the center. This electron wave was reflected by the surrounding cobalt atoms and produced a strong peak at the other focus as a result of mutual interference even though no magnetic atom was actually there. Eigler named this phenomenon a "quantum mirage."

This experiment implies that information generated from one cobalt atom located on one focus of an ellipse was delivered to another focus by electron wave—essentially suggesting a new information-delivery method in nanoscale. While optical communications have been widely used in the macro world, communications through electron waves may be realized in the nanosized world.

## 3 Japanese Pioneers

### (1) Kondo effect

The quantum mirage phenomenon incorporates the efforts of Japanese researchers to a significant extent. Actually, Eigler noted that the "Kondo effect" might explain the mirage phenomenon. The most famous among the physical phenomena named after Japanese researchers is the Kondo effect. This refers to the fact that, although electrical resistance in a metal usually falls in proportion to decreases in its temperature, it conversely increases when the metal's temperature becomes extremely low.

In 1964, Toho University Professor Emeritus Atsushi Kondo (then at the Electrotechnical Laboratory) theoretically demonstrated that such increases in electrical resistance were the result of the dispersion of conductive electrons under the effects of magnetic impurities contained in the metal. This phenomenon of increased electrical resistance is called the Kondo effect. According to Eigler, the quantum mirage is the result of reactions between magnetic cobalt atoms and conductive electrons—essentially the same mechanism as that in the Kondo effect. The discovery of the quantum mirage has resulted in a reevaluation of the Kondo effect as a fundamental theory relating to electrical conductivity in metals. As a result, Professor Kondo may become a candidate for the Nobel Prize.

Actually, a number of Japanese researchers have played important roles in the field of nanotechnology. In addition to Kondo, many Japanese researchers can be counted among the nanotechnology pioneers. The following presents several examples selected from the materials, information and biotechnology fields.

### (2) Metal nanocrystal alloys developed by Masumoto and Inoue

A representative achievement in the materials-related field is amorphous alloys and the next-stage nanocrystal alloys that were developed by Takeshi Masumoto (former director of the Institute for Materials Research at Tohoku University and currently director of the Electric and Magnetic Materials Laboratory) and Hisaaki Inoue (director of the Institute for Materials Research at Tohoku University). Both Masumoto and Inoue were awarded Citation Laureates by ISI (US), based on its citation index. This is regarded as an important indicator of objective evaluations among scientific researchers, as it indicates how often a scientist's work is cited in other research papers.[18] Masumoto was ranked sixth and Inoue second among Japanese scholars.

Amorphous materials are substances with a structure in which atoms are arranged without any regularity. While crystals maintain a stable state with the minimum energy, amorphous materials keep a meta-stable state at an energy level higher than that of crystals. This amorphous state can generally be obtained by rapidly cooling substances from a high temperature. For example, amorphous metals can be manufactured by spraying molten metal on a metal drum rolling at high speed.

Amorphous alloys manufactured in this way have a number of superior properties. They are, for example, stronger, more rustproof, and more easily magnetized than polycrystalline metals. Masumoto and his colleagues are recognized for their pioneering achievements in research on amorphous metals.

In 1984, Masumoto and Inoue produced an amorphous alloy comprised of dispersed nanocrystals by developing new composition and annealing processes. The product was three times stronger than duralumin, and Masumoto and Inoue reported that this strength was achieved by restricting crystal displacements (linear disorders in the atom configuration) that cause metal transformations within crystalline particles.[19] This is a successful example of controlling crystallization with a bottom-up approach, and can be evaluated as presenting an opportunity to realize one of the NNI's Grand Challenges—manufacturing a material that is lighter and stronger than steel.

### (3) Nanoparticles developed by Hayashi

Another example of the success of the bottom-up approach can be found in the gold nanoparticles developed by Chikara Hayashi of ULVAC Corporation (ERATO "HAYASHI Ultra-Fine Particle" project), for which part of the manufacturing technology is already at the commercialization stage. Although gold normally melts at 1,063˚C, gold nanoparticles (with a diameter of 5 nanometers or smaller) have a considerably lower melting point that allows them to start melting at around 527˚C. Nanoparticles are affected by their larger surfaces and present different melting points from those of bulk metals. When nanoparticles are assembled in a special process to prevent them from forming a large mass, they can maintain their lower melting points even when in a macrostate. A type of paste has already been developed to take advantage of this lower melting point, with expected usages involving printed-board processing at lower temperatures or with ultra-high precision.

### (4) Molecule beam epitaxy: Fujitsu's HEMT and Iga's surface-emitting laser

These stories of Japan's developments in the field of nanomaterials introduce some pioneers in the information-related area. Representative examples of nanoscale structures applied to information-related devices include the high electron mobility transistor (HEMT) and the quantum-well semiconductor laser.

If electrons are confined in two-dimensional space with a thickness level equivalent to that of a single atom, the speed of electron movement is accelerated by the quantum effect, etc. This makes it possible to realize high-speed devices as well as high-performance semiconductor lasers, as electron energy can effectively be converted into beams. Molecule beam epitaxy (MBE) was developed as a manufacturing method to realize such a structure, and efforts to develop MBE can be traced back to two different endeavors.

The first group to initiate work on MBE development included Dr. Leo Ezaki and his colleagues. Dr. Ezaki, a Nobel laureate in physics for his research on the tunnel diode, was working on the target of producing a thin-film that could generate tunnel effects when he started research on MBE soon after moving from Sony to IBM's Watson Research Center.

The second came from the efforts to develop the semiconductor laser. Izuo Hayashi of Bell Laboratories (currently a member of the Engineering Academy of Japan, who first succeeded in producing continuous oscillations in semiconductor lasers at room temperatures), his colleague, Dr. Morton Panish, and Dr. Zhores I. Aleferov of the Ioffe Physico-Technical Institute (Russia) had also started research aimed at drastically improving MBE properties in order to produce a steep hetero-junction (a junction comprised of semiconductors with different chemical compositions). For these efforts, Aleferov was awarded the Nobel Prize in physics, along with Dr. Ilby Herbert Kroemer (for his work on semiconductor hetero-junctions) and Dr. Jack St. Clair Kilby (the inventor of the integrated circuit).

The results of this research became highly significant as essential tools for nanotechnology research and technology development, and finally enabled Fujitsu Laboratories to successfully commercialize high electron mobility transistor (HEMT) technology by using an epitaxy method with atomic-level control provided by MBE. This HEMT technology has been used in the manufacture of high-speed electron devices with applications in satellite broadcasting. In addition, the surface-emitting laser invented by Kenichi Iga (former professor at the Tokyo Institute of Technology and currently director of the Japan Society for the Promotion of Science) is a highly rated achievement, as it has greatly improved the performance of traditional semiconductor lasers by using the quantum effect to become the most appropriate light source for optical communications of the future.

As shown by these developments, Japan has been a leader in the world in applying nanotechnology to information-related devices in terms of research and development, as well as in industrial use.

### (5) Sakaki's quantum-dot laser and Nakamura's blue laser diode

The research programs in the fields noted above are now being carried forward by using methods to contain electrons in one-dimensional space (a line) as well as zero-dimensional space (a dot). Compared with the development of two-dimensional structures that have been achieved with relative ease by the use of such technologies as MBE, however, the realization of quantum lines or quantum dots involves considerable difficulty. No practical method has yet been developed, and this remains an important priority issue in the field of nanotechnology. To resolve the problem, researchers are now trying to find solutions through two methodological approaches.

One approach involves the use of the miniaturization techniques that have been developed in semiconductor manufacturing. That is to say, two-dimensional structures are produced by the ultra-thin epitaxy method, and the resulting nanostructures within two-dimensional planes are reconstructed with miniaturization processing techniques. This process can be regarded as a convergence between the top-down and bottom-up approaches. At the laboratory level, miniaturization-processing techniques at the 10-nanometer level are becoming possible by the use of electron and ion beams. Single electron transistors with a one-dimensional structure have already been produced.

The second methodology relates to the use of bottom-up approaches concentrated on self-organization techniques, such as the deposition of ultra-fine particles at the time of thin-film. In a typical example, this approach involves depositing indium/arsenic nanocrystals on gallium/arsenic thin films to enable them to function as quantum dots. A quantum-dot semiconductor laser has been experimentally produced utilizing such self-organization techniques. Such a laser has demonstrated the characteristics that were foreseen by Professor Hiroyuki Sakaki of Tokyo University.

The discovery of the blue laser diode by Professor Shuji Nakamura of the University of California at Santa Barbara (a former employee of Nichia Corporation) was another example of the effective use of the bottom-up approach. For the gallium/nitrogen blue diode he invented, a model was proposed in which indium ions contained in the diode are self-organized to compose quantum dots, largely enhancing the light-emitting efficiency. If this model is correct, the Nakamura blue diode becomes effective by unconsciously applying a bottom-up approach to the invention.

### (6) Kishimoto's Interleukin-6

Keizo Kishimoto, rector of the University of Osaka, is clearly a Japanese researcher of prominence in the biotech-related technological field as he was ranked first in the Citation Laureate awards described earlier. Kishimoto discovered Interleukin-6 (IL-6), a messenger that plays an important role in the human immunization process. This is a significant contribution to the early diagnosis of cancer and the development of drugs for clinical treatment protocols, which the National Nanotechnology Initiative has cited as a major target.

Interleukin is a messenger in the immunization process that can activate the functions of cells. The element was named to signify the linkage between leukocytes (white blood cells), and its fundamental activity is to induce the production of antibodies. Without it, immunodeficiency diseases may occur because antibodies cannot be produced even if a virus invades the body.

It has been confirmed that Interleukin-6 is a physiologically active substance that triggers the broadest range of reactions among the 18 interleukins that have been discovered. And new medical treatments are now being established through genome research to produce drugs that block the combination of IL-6 and IL-6 receptors. In the area of IL-6-related immunization, a major feature of nanotechnology is clearly seen—namely through the cubic structure of the nanoscale molecule itself that clearly demonstrates its functions.

### (7) Nanotechnology and the Nobel Prize

As noted above, Japanese researchers have demonstrated significant pioneering achievements in all nanotechnology-related areas, including materials, information and biotechnology. This also substantiates the high potential of Japan's R&D activities in nanotechnology.

The Next Science and Technology Basic Plan of the Japanese government includes the specific target of earning about 30 Nobel Prizes for Japan during the coming fifty years. It is expected that Toho University Professor Emeritus Atsushi Kondo, who has made a significant contribution to the establishment of basic research relating to the quantum mirage theory, and several other nanotechnology scholars mentioned in this paper will join the list of such laureates.

# V What Nanotechnology Has Brought About

With reference to the important technological features of nanotechnology as discussed in Chapter III, let us consider the technological novelty of nanotechnology in more detail on the basis of its pioneering achievements.

## 1 Impact on Advanced Areas of Technology

### (1) Universality of nanotechnology

As shown in the achievements by pioneers cited in the previous chapter, a variety of new features emerge in the world of nanoscale structures that are different from those in macrostructure environments. Features that are unique to the nanoscale world can be seen in fullerenes, carbon nanotubes, ultra-fine metal particles (materials field), the quantum mirage, quantum-dot lasers (information-related field), interleukin and other immunizing drugs (biotechnology field).

In addition, it is also demonstrated that the bottom-up approach is commonly effective in the materials, information-related and biotechnology fields, as nanoscale functions can be built up to the macroscale level without disturbing them. In other words, nanotechnology can be recognized as a technology that provides a venue of encounter for each field in which progress has originally been made independently, and that also provides common guiding principles in carrying forward with R&D activities.

While the importance of the bottom-up approach was stressed previously, this by no means denies the importance of the top-down approach that is supporting progress in the current information-related technologies. Although the top-down and bottom-up approaches may appear to be in opposition, it is likely that a new paradigm may emerge as a result of the convergence of both approaches through the sharing of new guiding principles at the venue of encounter provided by nanotechnology. If technologies remain within a paradigm, they will inevitably face high walls that can be difficult to overcome. History provides ample examples that illustrate that only the creation of a new paradigm can achieve a breakthrough that conquers such obstacles.

### (2) Impact on material-related technologies

The impact of a new paradigm will not remain at the frontier of advanced technologies, and nanotechnology may exert an unexpected impact on areas where stagnation appears to prevail. Indeed, there is a good possibility of generating noticeable achievements in a short period of time by applying nanotechnology to fields where developments under the existing paradigm are inadequate.

In particular, developments can be expected in the materials-related areas. Current material development efforts have been successful in applying the top-down approach, such as high purification techniques, especially in the development of fine ceramics, new varieties of glass, and fine chemicals that are aimed at electronics applications, and medical and pharmaceutical usage. However, these efforts partly appear to run up against a wall. Although there are significant needs, the seeds to realize the necessary techniques are not fully adequate and the development methodologies are also underdeveloped.

If the methodologies and concepts of nanotechnology can be brought into such stagnant environments, major breakthroughs can be expected simply because nanotechnology is a treasure house that stores the seeds needed for the development of new materials. Combining the seeds of nanotechnology with the bottom-up approach may bring about a revolutionary methodology for the development of materials. Typical examples will include nanoparticle-applied products, ultra-hard metals containing dispersed ultra-fine particles, and carbon nanotubes.

Although the discovery of carbon nanotubes and the emergence of new functions are the result of nanotechnology itself, the manufacturing technologies for such products fall within existing techniques. And the efforts to commercialize these products have already been started. It is highly likely that other products or technologies are also being developed or commercialized.

### (3) Impact on information-related technologies

As described below, the integrated circuits currently in use are produced by a miniaturizing (top-down) technique that uses single-crystalline silicon manufactured by a method that can be interpreted as a bottom-up approach. This means that the convergence of the bottom-up and top-down approaches has already been realized—at least partially—in the field of integrated circuit technology. Nanotechnology is expected to further advance beyond the current partial convergence by achieving an even higher state of integration.

The roadmap for semiconductor memory (DRAM) projects that the design rules (minimum line width) for DRAM chips will reach 100 nanometers in 2005, and 70 nanometers in 2008 (see Figure 1). As noted earlier, a number of technological difficulties can be expected when such miniaturization advances and the size of a unit memory device approaches the nanoscale level.

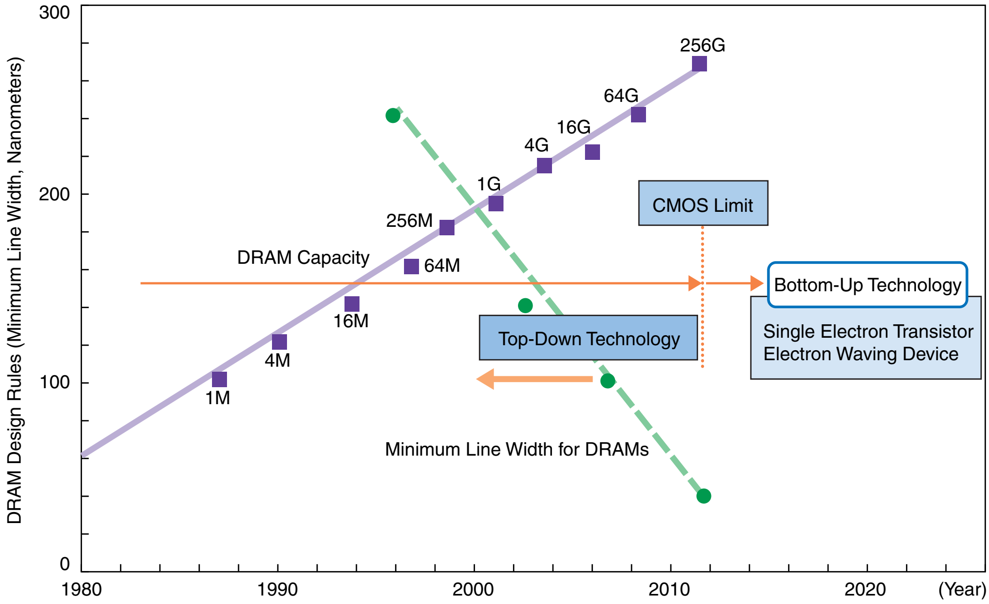
For example, it is likely that the wave-like nature of electrons would disturb the functions of the field-effect transistor, a unit device of the present integrated circuit. Or the insulator thin-film would become too thin to maintain its insulating function.

Of course, it may be possible to temporarily extend the miniaturization even further under a top-down method by designing a device structure that could control the wave-like nature of electrons, or by developing even thinner insulator layers that can still maintain their functions. In place of such a concept, however, nanotechnology would suggest that it is essential for the future development of information-related technologies to create nanostructure devices based on the quantum effect (e.g., single-electron transistors) and to develop techniques to assemble such devices using bottom-up techniques.

### (4) Impact on biotechnologies

In his remarks cited earlier, Feynman predicted that greatest impact of physics on bioresearch would occur through the invention of high-resolution electron microscopes that can directly identify and observe each single atom, rather than applying theoretical analysis based on quantum

**Figure 1. Roadmap for Semiconductor Memory (DRAM)**



Notes: CMOS = complementary metal-oxide semiconductor; DRAM = dynamic random access memory; G = Gigabit; M = Megabit; nm = nanometer.
Source: Nomura Research Institute.

mechanics to biotechnology. As he predicted, the invention of the scanning probe microscope has proven immeasurably valuable in moving biotechnology forward, including DNA analysis.

While these measuring techniques have partly achieved some results, they are expected to further advance mainly in the field of information-related devices and materials, and to be widely applied to various biotechnological areas to support the development of biotechnology.

Similar examples include the "DNA-chips" (an element that realizes DNA separation based on the difference in dispersion speeds in fine-pitch grooves on quartz glass substrates), which is manufactured with a miniaturization technique developed for semiconductors and optical devices. DNA-chips are expected to contribute considerably to the discovery and development of new drugs, protein synthesis and other new techniques. In addition, a multiplier effect may occur in biotechnology as bottom-up methods developed for biotechnology would be applied to information-related areas and could be reapplied to biotechnology after undergoing new improvements and refinements. In short, the fact that nanotechnology provides common basic technical features in all related fields opens up a host of potential benefits in a wide variety of venues.

## 2 Bottom-Up Approach

Let us examine more specifically how the bottom-up approach will work in the future.

### (1) Two bottom-up approaches

In order to achieve the ambitious objectives included in the statement of President Clinton (see Table 4), the bottom-up approach is essential. The problem is what kind of bottom-up approach should be followed. There are two possible approaches.

One is an approach to utilize the features of existing nanostructures. In this case, nanostructures existing in nature are observed to induce the emergence of their inherent characteristics. These characteristics are assembled to compose macrostructures based on predetermined designs (modeling process) to realize functional materials or devices (see the white solid arrows in Figure 2). The artificial development of nanostructures not existing in the nature is the second approach. In this case, the process will start from the design of nanostructures (see the black solid arrows in Figure 2).

Examples of the first approach include the following biotechnology cases. DNA structures existing in human

**Table 4. Targets of NNI's Grand Challenges**

(1) Containing the entire contents of the Library of Congress in a device the size of a sugar cube.

(2) Making materials and products from the bottom-up, that is, by building them up from atoms and molecules. Bottom-up manufacturing should require less material and create less pollution.

(3) Developing materials that are 10 times stronger than steel—but only a fraction of the weight—for making all kinds of land, sea, air and space vehicles that are both lighter and more fuel efficient.

(4) Improving computers by improving the speed and efficiency of minuscule transistors and memory chips by factors of millions, thereby making today's Pentium IIIs seem slow.

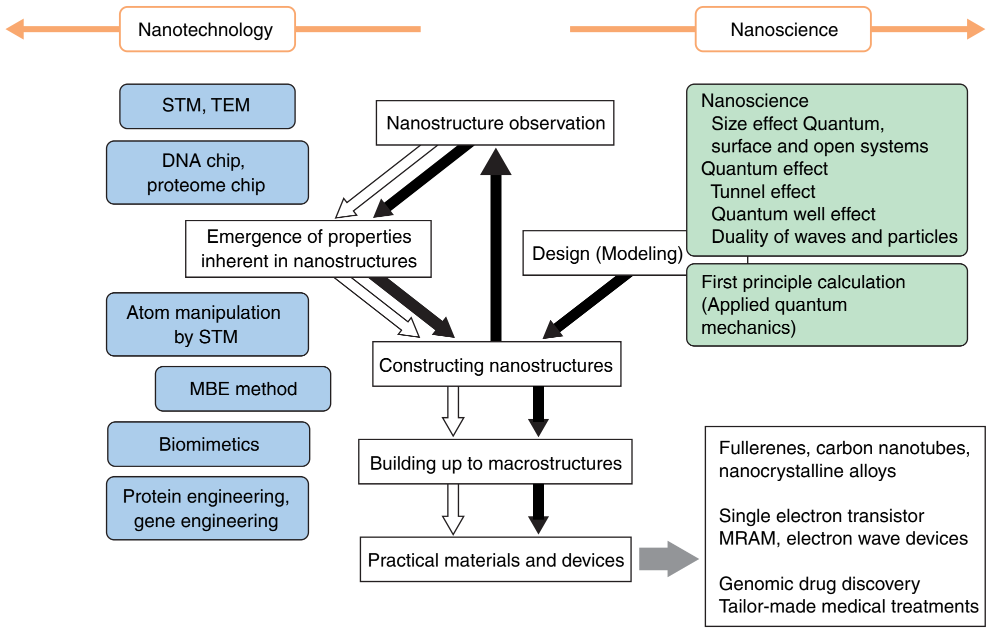
(5) Detecting cancerous tumors that are only a few cells in size using nano-engineered contrast agents.

(6) Removing the finest contaminants from water and air, promoting a cleaner environment and potable water at affordable costs.

(7) Doubling the energy efficiency of solar cells.

Source: National Science and Technology Council, "The National Nanotechnology Initiative: The Initiative and its Implementation Plan," June 2000

**Figure 2. Process for Realizing Nanodevices**



Note: MBE = molecule beam epitaxy; MRAM = magnetic random access memory; STM = scanning tunnel microscope; TEM = transmission electron microscope.
Source: Nomura Research Institute.

body are analyzed (by X-ray) to find nucleotide sequences (by the electrophoresis method). Relations between proteins having unique properties and DNA sequences are established (by proteome chip, etc.). Based on such knowledge, proteins are to be synthesized with new functions by means of self-multiplication.

Examples of the second approach include quantum devices. In the first place, a theoretical size effect (quantum effect) is predicted on the basis of quantum mechanics (applied quantum mechanics) in designing a nanostructure having the desired properties. As the next stage, the designed nanostructure is actually composed (by MBE, lithography methods, etc.) and the completed structure is measured (by STM, TEM methods, etc.) to confirm that the desired properties are actually realized. Finally, the nanostructures are assembled to form a macrostructure to realize a new functional material or device.

### (2) Current situation of bottom-up approach

With respect to new structures or devices acting in the nanoscale realm, researchers have already come up with several new ideas, such as the nanoparticle, quantum dot, single electron transistor, quantum mirage, and DNA. What, then, is the current status of methods to build up a single nanotechnology device or to assemble nanostructures to the level of functionality?

For functional materials, techniques to build up single crystals have already been developed in assembling materials at the atomic or molecular level into a macroscopic structure. As the first step in this technology, the composition of the materials is determined and these materials are kept in a thermal state to facilitate the growth of crystals with the minimum energy through the natural process. (In this sense, the single-crystal build-up technique has been using the bottom-up approach without any conscious decision to do so.) While crystalline materials including silicon have been widely used as electron device materials due to their excellent properties, only the emergence of high-quality and large single crystals has led to the current success in LSI (large-scale integration).

The epitaxial thin film introduced in the section on pioneers is a fruit of the development of the epitaxial growth method (a single-crystal growing technique). This epitaxial growth technique can deposit single-crystal thin films with different compositions in a sequence of layers, one upon another, thus making it possible to produce nanostructures in the vertical direction of the thin-film thickness. It is believed that this technique will play an important role in the deployment of bottom-up technologies in the future. Moreover, researchers are now trying a number of methods to deposit ultra-fine particles under specific conditions, although adequate control capabilities covering such sizes and spatial distribution are still lacking.

It may of course be difficult to achieve all the objectives relating to the nanoscale build-up process by applying such techniques only, and other assembly techniques that differ from those described above are now starting to appear at the experimental level. For example, there is a technique to pick up single atoms one by one as demonstrated in the case of the quantum mirage, and to arrange them in the desired position. Another is a technique to capture and move single atoms by using laser beams as “tweezers.” However, it is very difficult to manufacture practical devices or functional materials by these techniques, as obstacles relating to mass production are still hard to overcome—at least for the moment.

### (3) Bottom-up approach in the future: Biomimetics

Considering the current issues facing nanotechnology, it is necessary to develop practical technologies to assemble functional units into a desired structure, as in the case of crystal growth. Without this, the bottom-up approach will remain an interesting scientific idea—far from becoming a true technology that will exert a significant impact on our lives. No clear answers are yet available regarding questions on how to deal with such challenges. That is precisely why people label nanotechnology as no more than a challenging technology of the future, because it may require a long period of time for commercialization. Accordingly, how can we find the solutions necessary to respond to these questions?

It is now considered that the answers may be found in biotechnology. Living organisms originally emerged on earth under specific conditions (temperature, pressure, ultra-violet light, etc.), and the first organism was accidentally synthesized from oxygen, hydrogen, carbon and other elements. These original organisms have increased through the self-multiplication process, developing through many eons into the wide diversity of species living today. An essential feature of each organism is its built-in function to multiply by copying itself.

At present, a major part of the phenomenal mechanism that occurs at the nanoscale level has already been made clear—a series of base units make up a gene, which is then copied on the basis of chemical interactions and which successively self-multiplies. Scientists believe that these basic principles of each organism contain ideas to identify methods with which nanostructures having the desired functions can be caused to grow on a self-replicated basis, and that such structures may compose functional materials or devices of a macroscopic size. As indicated by the National Nanotechnology Initiative noted earlier, nanotechnology has an aspect common to biomimetics that simulates the features of organisms. It is likely that such a direction is a key to making the bottom-up approach an effective technology.

## VI Realizing Nanotechnology

If the emergence of nanotechnology is considered to be an opportunity for a paradigm shift in leading-edge technologies in various fields, there is a great possibility that the development of nanotechnology will usher in a new paradigm with respect to new research and development and the management of technological development as well. Conversely, it would be impossible to efficiently promote nanotechnology without drastically reforming current research and development management.

## 1 Reform of the Research and Development System

The characteristics of nanotechnology that must be taken into account in considering a reform of the research and development system include: (1) nanotechnology is a common infrastructural technology that covers a wide range of fields and is likely to generate substantial synergistic effects among research themes; (2) there are many technologies that require a long incubation period before they become available for practical use; and (3) as symbolized by the usage of applied quantum mechanics, a high degree of professional expertise is required to understand the essentials.

Because of this background, research and development in nanotechnology generally requires large-scale undertakings and extended research periods, both of which inevitably lead to increased research and development costs. In addition, there are many cases in which—unlike what is commonly done under the current system—it is not possible to clarify the scenario for recovering R&D investment by monopolistic marketing in the course of nanotechnology development. This means that the current concept of in-house research and development, in which all processes from R&D to commercialization are handled within one company in the hope of generating profits that exceed research costs, may very well not work.

The existence of in-house research facilities predicated on the assumption that all processes should be handled within one company is rather transient from a retrospective viewpoint. This thinking is clearly dated in the eyes of many, as more and more leading companies are turning to new approaches towards R&D that are based on outsourcing and partnerships, including patent cross-licensing, etc.

As nanotechnology develops, these trends will be further strengthened. For example, outsourcing and/or establishing partnerships for research and development and commercializing intellectual property rights to recover research and development investment before setting up business operations on the basis of such rights is expected to become increasingly common in the future.

## 2 Expectations for the Government

Viewed from a different angle, this means that the role of public organizations, i.e., the involvement of the government, takes on a new importance in the promotion of nanotechnology. Specifically, government measures concerning nanotechnology should focus on the following three areas.

### (1) Review of science and technology budget allocations

The first relates to a comprehensive review of the government's budget allocation ratio for science and technology, including the nuclear power and space development fields. The NNI led to an increase in the budget for nanotechnology and about ¥50 billion in appropriations for the initial year. This amount included almost no funds for information-related technologies, which is treated as a mainstream current in the development of nanotechology in Japan. This situation was essentially the same as that concerning the NNI budget for biotechnology that was previously discussed.

In other words, there are not a few cases in the US in which research in areas that could be included in nanotechnology, based on the characteristics of the target technologies for research and development is handled outside the framework of the NNI budget. Moreover, as pointed out in discussing the federal budget, the scale of such individual budgets is far greater than the NNI budget.

While Japan intends to appropriate about ¥50 billion annually (the same level as in the US) to nanotechnology-related research, this also includes funding for semiconductor developments. In view of this situation, substantial budgetary increases would be required for nanotechology in order to promote its development in competition with the US in the future. However, it is obvious that Japan's recent financial straits will not allow any major increases in the budgets for science and technology. Accordingly, a comprehensive review of the allocation ratios among science and technology funding is required, for which the leadership of the Cabinet-level Council for Science and Technology Policy is sorely needed.

### (2) Enhancing human resource development measures

The second concerns the enhancement of measures pertaining to human resource development. This is a matter of major importance for nanotechnology development, as nanotechnology includes development themes that must be dealt with over a long period of time and which also require human resources with expertise in a wide range of fields.

In view of this background, it is desirable to network research groups that are dispersed among various universities and research institutes by following the NNI approach in establishing a structure that efficiently promotes research and development in nanotechnology while maintaining the independence of each group, and in incorporating a system that strongly promotes human resource development within such a structure. For example, a network linking postgraduate schools can be established under this structure, and specialists can provide video lectures for each specialized field dealing with atoms, bits and genomes.

In addition to such lectures, it is also effective to establish a new center offering training in the technologies needed for nanotechnology developments. This is because a number of personnel who are well acquainted with various highly specialized technologies—including measurement apparatuses such as STM, modeling by computer, micro-lithography, MBE and other manufacturing technologies—are essential for nanotechnology.

The present postgraduate education system in Japan strongly emphasizes on-the-job training, in which students are assigned to a single laboratory or group for an extended period of time. If a networked education structure were adopted, it would be possible to compensate for the defects of this current system by developing human resources with wider insights and more extensive knowledge.

### (3) Reforming the management of public research institutes

The third focus for the government involves reforming the management of public research institutes and universities in order to effectively utilize the funds invested. More specifically, it would be necessary to improve the consciousness of the management personnel responsible for these organizations with respect to cost performance, and to fully pursue the principles of basic economics.

For example, one type of management reform at a university would be to consign the management of the training center to the private sector and to pursue economic efficiency. These approaches do not necessarily represent abrupt departures from current practices in all cases, especially when we consider such current moves as outsourcing the preparation of questions for university entrance examinations to private companies or establishing companies that provide administrative management for universities on a contract basis. In any case, management reform is expected to be realized from 2001 to 2003, when plans to reform such governmental organizations into independent administrative institutions are implemented.

## 3 Cooperation Involving the Government, Industry and Academia

What is important for Japan is how to clarify role sharing among private industry and public research organizations and to strengthen cooperation among the government, industry and academia. Research organizations associated with each sector have different missions and roles, as well as their own values and goals based on their respective principles. And while the values of these organizations do not necessarily need to be identical, some fundamental principles should be commonly shared to maintain effective cooperation. In particular, the following two priorities must be shared.

The first is the need to cultivate an attitude that pays greater attention to cost performance in research and development activities. As noted earlier, public research organizations funded by the taxpayers have an obligation to clearly recognize the importance of cost performance.

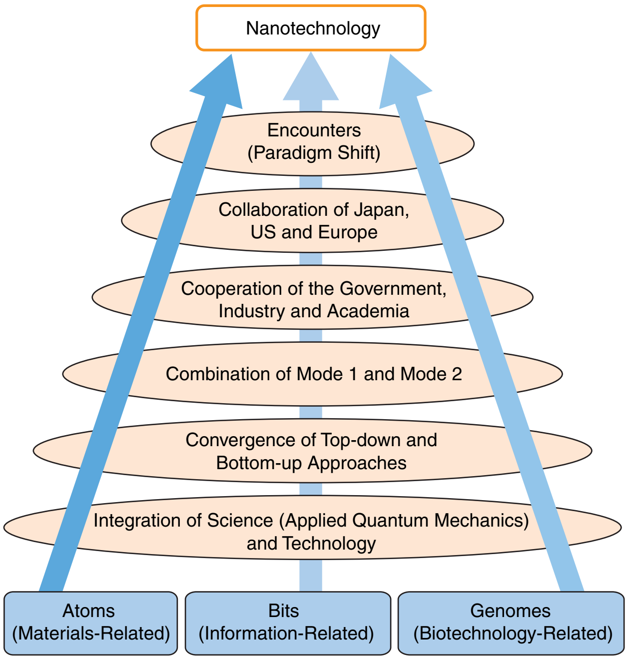
The second relates to intellectual property rights stemming from R&D activities. As R&D efforts in nanotechnology are pursued in a wide range of industries, it is desirable for private industry to regard intellectual property as public goods. For that purpose, the commercialization of intellectual property rights should be accelerated in early stage.

At the same time, while public organizations have traditionally recognized the concept that intellectual property rights belong either to individuals or to the government, they should also make some concession to accept the general practice in private industry that intellectual property rights belong to organizations. Otherwise, it might be difficult to establish stable and long-term contractual relationships between public and private organizations.

It is obvious, of course, that compensation systems to specifically evaluate the achievements of inventors are necessary by, for example, introducing or improving licensing fee systems. If such systems are improved, they may provide a better motivation to researchers—and may further be justified from the viewpoint of enhancing cost performance.

In promoting cooperation among the government, industry and academia, it is important that R&D activities combine the Mode 1 and Mode 2 models as defined by

**Figure 3. Flow Towards Nanotechnology Developments**



Source: Nomura Research Institute.

Michael Gibbons.[20] Mode 1 refers to activities developed in closed, individual academic settings motivated by the curiosity of the individuals involved, whereas Mode 2 refers to activities concurrently developed in multiple academic environments with problem-solving—i.e., commercialization efforts—as the driving force. It is expected that these two modes will evolve in a close interrelationship and on a combined basis in many cases under the cooperative relationship linking the government, industry and academia.

This paper has so far described the major impact that nanotechnology exerts on various R&D activities and the measures needed to develop it further. Figure 3 summarizes the various background factors that influence nanotechnology research.

## VII How to Deal with Nanotechnology

Finally, we offer some suggestions to private industries on how to accept or deal with nanotechnology. While some of these concepts have been described earlier, they should be reiterated in view of their importance.

### 1 Encouraging Nanotechnology

The first requirement is to actively deal with nanotechnology—in other words, to accept "the encouragement of nanotechnology." As changes take place in general business environments, the progress of nanotechnology provides companies with significant opportunities as well as threats. The opportunities will come to us through the ability of nanotechnology to generate business resources and make them more broadly available; the threats will arise as nanotechnology may result in paradigm shifts that are likely to make existing resources outdated. We suggest that if a paradigm shift is inevitable, however, companies should positively react to nanotechnology to take advantage of the opportunities that may be produced during such shift.

### 2 Maintaining a Broad Horizon

It is important to maintain a broad outlook in terms of time and space. In the effort to commercialize technologies, it is necessary to both search out and follow up on a wide range of technical seeds with an attitude that calls for visualizing and analyzing the development of such seeds over a long span of time. Generally speaking, technologies for which a number of applications can be expected tend to require a long development period, as such developments tend to be diversified and a large amount of investment is necessary.

In the case of the carbon nanotube that plays a symbolic role in nanotechnology, for example, a diverse array of applications is waiting for commercialization. If such applications are to be actually realized, the careful selection of subjects or projects is necessary. And for that purpose, a wide perspective covering entire fields of nanotechnology is required. Many companies in this country have seen not a few cases in which inefficient investments were actually made in the past while riding the waves of technological or scientific research booms. Such failures must not be repeated.

The impact on nanotechnology from the outside world should also be taken into consideration. For instance, progress in information technology, including advances in computer software, may significantly affect developments in nanotechnology, as IT supports both design and analysis work in such research.

### 3 Innovations in R&D Management

Industries should quickly respond to the innovations in business management brought about by nanotechnology. As noted earlier, a technological paradigm shift caused by nanotechnology may give rise to other paradigm shifts relating to R&D management, such as the treatment of intellectual property rights or whether research and development efforts should be pursued by individual capabilities or group efforts. Every organization must promptly respond to these changes.

Industries should also be careful not to treat R&D activities as a sanctuary. In the process of nanotechnology development, the distance between research and business activities tends to be narrowed, as indicated by cases in which science directly becomes technology or intellectual property rights themselves become the subject of new business projects. In other words, as research strategies and business strategies must be tightly knitted in nanotechnology, management should have a direct connection with R&D sections and at least have adequate knowledge of what's going on in the labs.

As explained earlier, it is important for R&D sections to develop a better awareness of cost-performance among staff members—something that already takes top priority in business sections. If this is achieved, the company can effectively determine whether or not it is reasonable to carry out all activities (from R&D to commercialization efforts) within the company, and can build up R&D systems meeting its business objectives in advance of other companies.

R&D management within a company should also take special care in securing and training human resources, as nanotechnology is a long-term organizational task. As a number of new seeds can be expected to emerge and quickly become outdated in nanotechnology, the specific capabilities of researchers may become exhausted in a relatively short period of time. Accordingly, industries should concentrate on human resource strategies with even greater attention than before in order to develop sustainable human capabilities.

## 4 Positive Search for Business Opportunities

Industries should have a wide perspective to find new business opportunities not only in the field of nanotechnology itself, but also in other fields surrounding nanotechnology. For example, opportunities to deploy R&D support businesses and venture businesses should be sought.

Semiconductor and information industries have also helped peripheral businesses grow, and in turn have been supported by these peripherals. During the process of nanotechnology commercialization, it is likely that a number of peripheral companies would be developed. Technologies for the support of R&D activities are highly likely to lead to such peripheral companies, especially if such technologies are developed by a company's own research and technical development efforts. Just as peripheral companies in the semiconductor industry are not necessarily engaged in semiconductor technologies, peripheral companies surrounding nanotechnology may not be involved in nanotechnology itself.

In addition, it is possible that technologies developed to support a specific nanotechnology development may be used for areas other than nanotechnology. Although support technologies and related businesses are mostly involved in measuring and control techniques as of this time, such specialties as testing, examination and maintenance may become possible areas in the future as practical applications make progress.

It was pointed out earlier that the commercialization of nanotechnology requires extensive management and R&D resources. However, challenging opportunities involving venture businesses that do not require substantial investment can also be found in nanotechnology. In actuality, a large number of ventures have emerged in response to the appearance of new seeds in the semiconductor and information industries, which are similar in nature to nanotechnology. It can be expected that such a trend may be even more pronounced for nanotechnology.

There are three reasons for such an expectation. The first relates to the rapid changes in Japan's cultural climate in which venture businesses have traditionally been difficult to nourish, mainly because of the changes occurring in the academic world. Second, venture capital can be rapidly raised for promising new technologies. And third—even more strongly in nanotechnology than in semiconductors—the items necessary for carrying out business are purchased from other companies rather than being manufactured by the companies using them. Accordingly, there will be many opportunities for companies specializing in specific products or services to start up business relatively easily.

In any case, the challenges facing nanotechnology ventures will no doubt provide great opportunities for the entire range of Japan's government, industry and academia. If such challenges can successfully be met, industries may gain new possibilities and capabilities.

This paper has outlined the short history of nanotechnology from its beginning to the current time. However, the real impact of nanotechnology will start to appear mainly from this point forward, as nanotechnology begins to open the doors to many new opportunities in the bright and promising society of the future—which I plan to describe at another opportunity.

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