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Analysis of Japan's Nanotechnology Competitiveness — Concern for Declining Competitiveness and Challenges for Nano-systematization —

Daisuke Kanama
Nanotechnology and Materials Research Unit
Akio Kondo
1st Theory-Oriented Research Group

1 Background and issues

Japan is generally believed to be strong in nanotechnology, but is it true?

The beginning of the promotion strategy for the nanotechnology and materials field in the "Third Science and Technology Basic Plan"[1] states, "Japan's materials technology, because of decades of unstinting effort and research by many researchers and research organizations, is firmly established at the world's highest level for all stages, from basic to applied research to practical application of raw materials and component materials, making them the source of the global competitiveness of Japan's domestic manufacturing." This statement, however, applies to materials technology alone. Although the strategy states that nanotechnology ("nanotech") is also at the world's highest level, it says, "the source of Japan's strength in nanotechnology is its strength in materials technology." Some perceive that the strong materials field drives nanotech, rather than the entire nanotech field itself being strong. Focusing on nanotech alone, an increasing number of nanotech experts are experiencing a sense of crisis or a feeling of being stymied regarding Japanese nanotech.

Where do these experts' feelings come from? And on what basis can one claim that Japan is strong in nanotechnology in the first place? Based on research papers, patents, and survey results, this article intends to discuss, by examining nanotech's technological characteristics and industry structures, Japan's nanotech competitiveness and changes in the competition stages of nanotech, which are both difficult to grasp through quantitative analysis alone. Although an examination of factual data on research papers and patents may suggest that Japanese nanotech is in a superior competitive position, the country is likely to face serious problems in the future when nanotech undergoes full-fledged commercialization and its stages of competition shift. The authors address these issues by centering around the term "systematization."

Recently, nanotech has generally been defined as technology dealing with scales from 1 to 100 nanometers. In the above-mentioned promotion strategy for the nanotechnology and materials field, the nanotech that should be promoted by the national government is "technology that breaks away from traditional principles or conventional wisdom to open up new worlds of science and technology, enabling not only dramatic advances but also potentially strengthening industrial competitiveness and creating new industries[1]." In this context, the strategy calls the nanotechnology meeting such criteria "true nano." The strategy further states that where nanotechnology is technology that aims to utilize phenomena and characteristics whose expression is peculiar to the nano world, "true nano" is defined as a kind of nanotechnology encompassing the following:

- Creative R&D expected to bring discontinuous progress (jump ups) rather than extensions

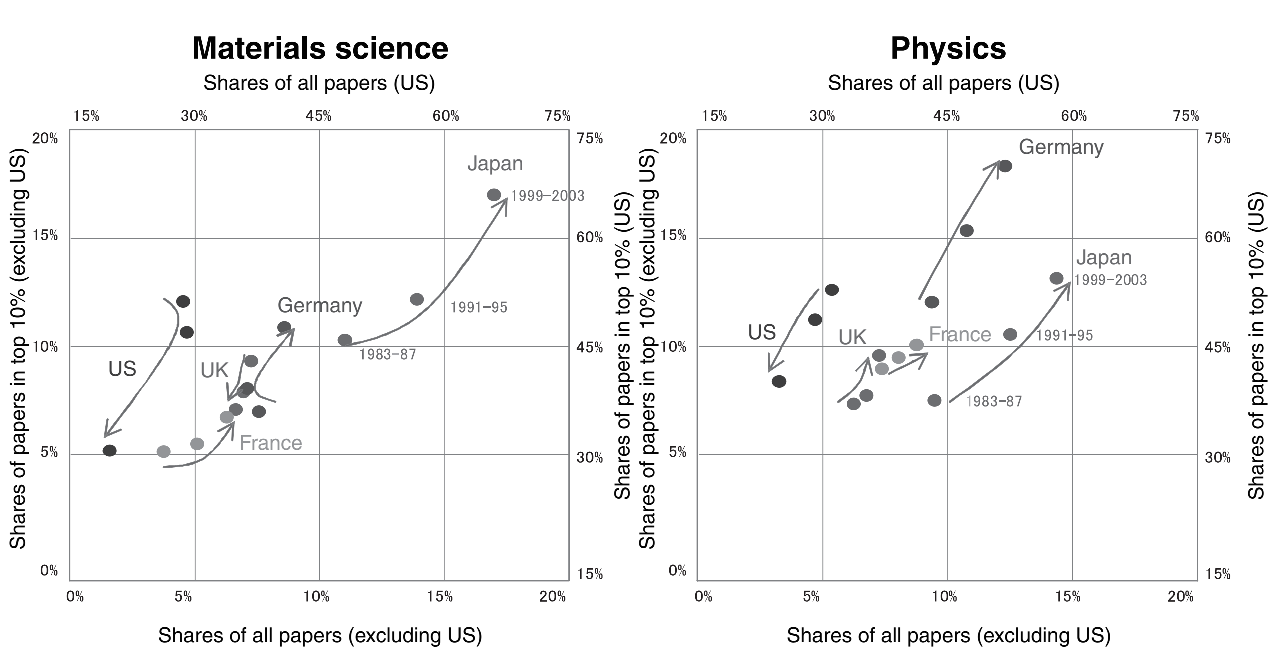

Figure 1 : Materials science and physics papers as a share of all papers and of papers in the top 10% in major countries over 20 years[2]

of conventional technology, and,

– R&D with a great potential for significant industrial applications.

In other words, future nanotech is not merely the extension of miniaturization technology below the 100-nm level, but instead is nanotech that will help create new industries and strengthen industrial competitiveness. This report adopts the same definition of nanotech.

2 Quantitative analysis of elemental science and technology: based on papers, patents, and Delphi survey

2-1 Analysis of research papers

It is difficult to quantitatively analyze nanotech research results from papers. Nanotech is an interdisciplinary field, and with the exception of recently-started journals such as Nature Nanotechnology, there have been no journals specializing in the nanotech field. Analysis of recent nanotech journals alone will thus not provide data sufficient in terms of quality or quantity*1. In order to find the results of basic research in nanotech, the authors therefore turned to materials science and physics because of their strong characteristic as fundamental disciplines of nanotech.

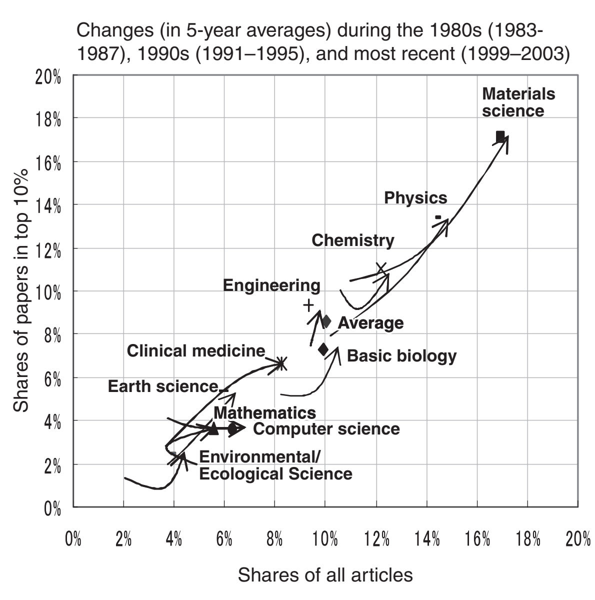

Figure 2 : Papers in various fields as a share of all papers and papers in top 10% in Japan over 20 years[2]

1. Basic biology includes agriculture, biology/biochemistry, immunology, microbiology, molecular biology/genetics, neuroscience/praxeology, pharmacology/toxicology, botany/zoology.
2. The bottom end of the arrow indicates the 5-year average for 1983–1987; the point indicates that for 1999–2003.

Based on analysis of research papers in materials science and physics, Japan is next behind the leader US in terms of both total number of research papers and the top 10 percent most-cited papers, with exception of the top 10 percent most-cited papers in physics, and the gap is narrowing every year. (See Figure 1.) In materials science in particular, Japan is well ahead of all other countries except the US. Looking at various fields in Japan as well (see Figure 2), Japan's strength in chemistry as well as in materials science and physics is apparent.

2-2 Analysis of patents

The patent application situation of various countries can be found through keyword searches related to nanotech and its applied technologies. The authors classified patents according to the nationalities of applicants for patents submitted to four major patent offices: the Japan Patent Office, the US Patent and Trademark Office, the European Patent Office, and the World Intellectual Property Organization (WIPO). Figure 3 shows a comparison of applicant nationalities in 2003-2005 for the 10 countries with the most applications[4-5]. In 2005, there were approximately 6,700 US nationals, the highest number, with Japan second at about 4,200, with all other countries well behind. Looking at changes over time, both Japan and US nanotech-related patents are increasing significantly.

In 2005, however, three of the top five organizations applying to the Japan Patent Office were public research institutions[4].

2-3 Japan's R&D level according to a Delphi survey

In 2004, a Delphi survey conducted by the National Institute of Science and Technology Policy asked specialists in individual science and technology disciplines to rank Japanese research and development versus the US, Europe, and Asia in one of five levels from "leading" to "behind"[6]. Figure 4 shows the results versus the US and Europe. The numbers in the axes of the chart represent the values numerically indexed from the responses received for the five levels. The survey specifies 10 areas of emphasis*2 in the nanotech/materials field. Almost all these areas

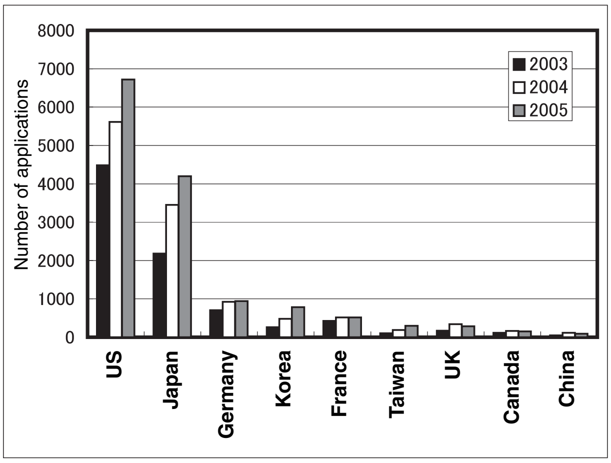

Figure 3 : Nanotech patent applications submitted to the four major patent offices [JPO, USPTO, EPO, WIPO], by nationality

Prepared by the STFC based on References[4,5]

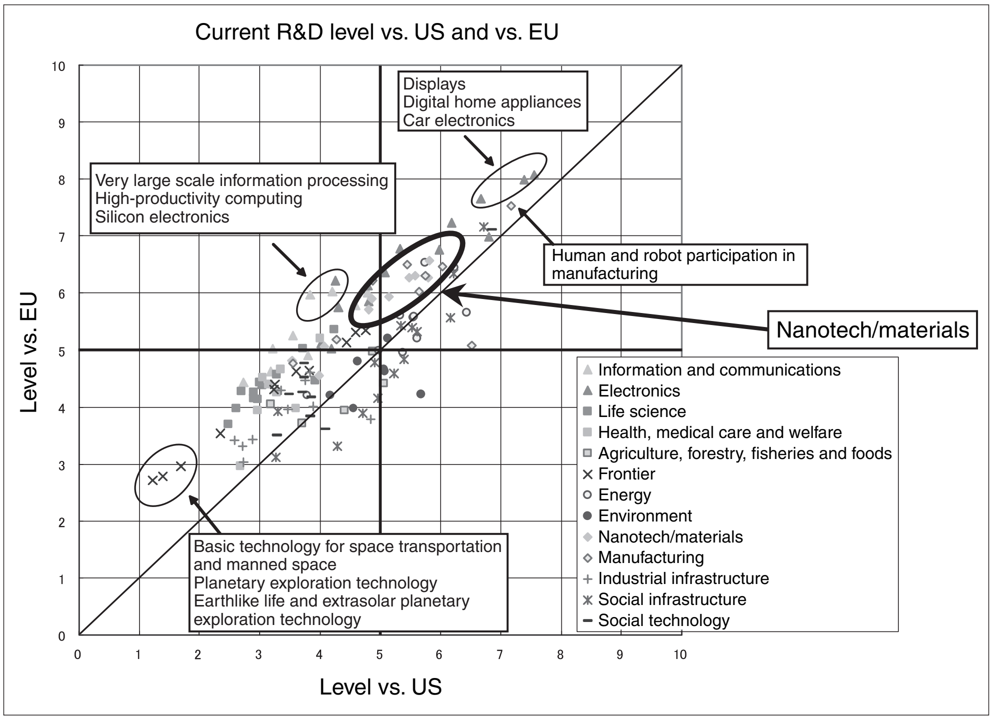

Figure 4 : Japan's R&D level according to Delphi survey[6]

are located in the center of the chart or slightly higher. In other words, the level of Japanese nanotech/materials development is seen as somewhat leading or even with that of the US and somewhat leading that of EU countries.

2-4 Potential of Japanese nanotech as revealed by quantitative evaluation

The above results confirm to some extent the stereotyped view that "Japanese nanotech is strong." These data, however, may demonstrate that Japan's strength lies in individual nanotech areas. In this sense, one can say that Japanese nanotech has great potential. With some exceptions, however, the technical seeds of nanotech have not been commercialized. From the perspective of technology, it may therefore be premature to evaluate the international competitiveness of nanotech as a whole. Beginning in the next section, the authors discuss the potential of Japanese nanotech, focusing on the competing technical areas and their changes that nanotech R&D will probably face in the future.

3 Technical characteristics of nanotech and challenges for nano-systematization : facing increasing technological uncertainty

3-1 Outlook for nanotech R&D in the future

Figure 5 shows nanotech technical levels and times to commercialization as described by M. Roco, who has spearheaded the National Nanotechnology Initiative (NNI) in the US[7]. This chart depicts progress beginning with the first generation: passive nanostructures expressing previously unknown functions as a result of improving microfabrication technologies for conventional materials. The second generation is active nanostructures gradually expressing new and original functions at the nanolevel that affect other materials and systems. In the third generation, these new nanolevel functions become original systems expressing new mechanisms. Finally the fourth generation is nanosystem materials designed at the atomic or molecular level as molecular devices in which nanolevel molecules express their intrinsic functions*3. Technology examples in the first generation include coatings, nanoparticles, and nanostructured metals. In the second generation, they include targeted drugs, environmentally adaptive structural materials, and actuators. Third-generation technology examples include three-dimensional network structural materials and supermolecule materials. In the fourth generation, technology examples include molecular devices designed at the atomic or molecular level as nanosystems.

3-2 Technical characteristics and challenges: from top-down technology to bottom-up and nano-systematization technology

Figure 5 presents possible challenges that nanotech should tackle. As is often said, research in physics, chemistry, and materials science in the US targeted nanolevel problems long before the Federal Government began promoting nanotech. However, they were merely handling bulk materials, "aggregate" that included nanoscale structures. Although scanning tunnel microscopes (STM) and self-organization technology have recently enabled some extent of molecular-level control, perfect control and assembly at the nanoscale level remains problematic. Here is where the true challenge of nanotech awaits. Structures designed and systematized at the molecular level could become materials completely different from conventional materials in terms of functions and characteristics. This is called "the technological uncertainty of nanotech."

Conventional technological uncertainty is understood to be a phenomenon where miniaturization approaches physical limits, with quantum effects appearing. The technological uncertainty of nanotech, on the other hand, is a situation in which one is completely unsure how to assemble structures designed and systematized at the molecular level, or what kind of functions such nanosystem materials might express if they were assembled. Taken to the extreme, an infinite number of microstructure materials and corresponding assembly and control technologies are conceivable, theoretically resulting in an infinite number of potential nanosystems.

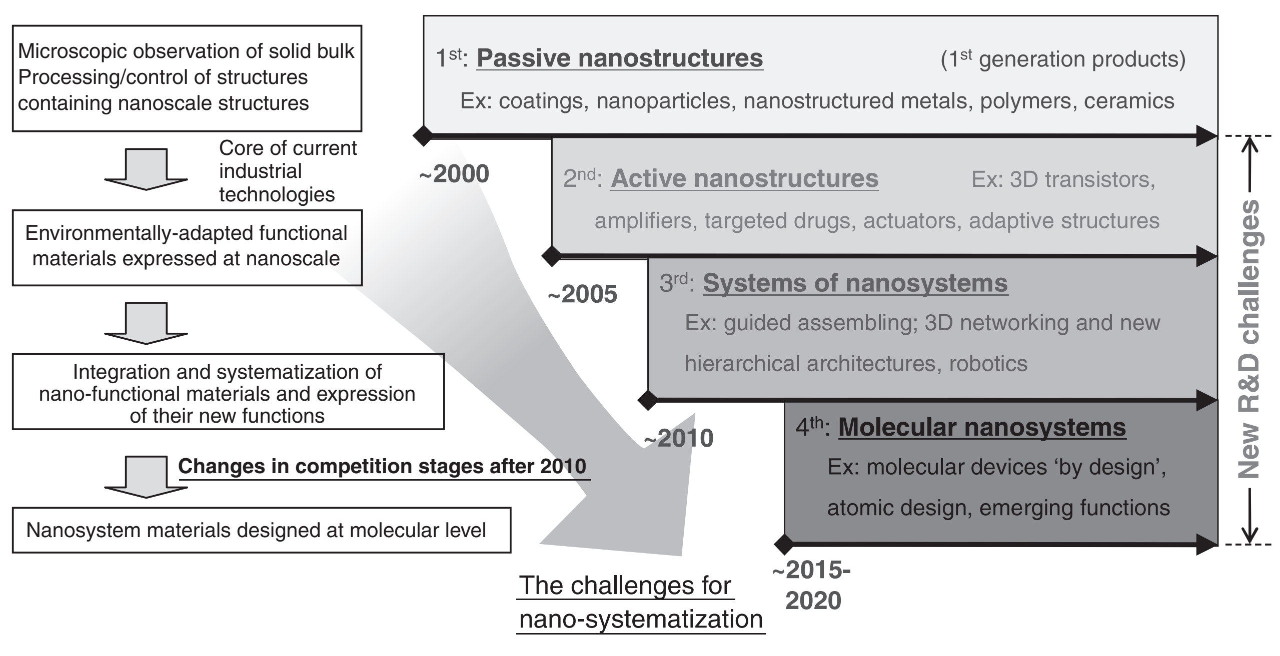

Figure 5 : Roadmap for nanotech development

Prepared by the STFC based on Reference[7]

Nanotechnology and nanoscience

Conceivable categories of nanoscience include measurement of unknown properties of existing substances (e.g., measurement of electrical conductivity, temperature dependency, etc.), structural analysis of new materials and elucidation of the interdependency of new materials, and development of computation methods for nanosimulation. With "nonlinear model-based" R&D becoming the mainstream today, mutual feedback between nanotechnology and nanoscience is extremely important. Nano-systematization discussed in this article is more closely associated with technology than science because of its significance in the context of commercialization. However, because of the technical complexity of nanosystems, nano-systematization will inevitably need support and feedback from nanoscience.

In the nanotech field, the former type of technological characteristic centered on miniaturization is generally called top-down technology, while the latter, which aims to fabricate nanosystems, or to achieve nano-systematization, is called bottom-up. In other words, technical development that aims to improve materials function through repeated scaling down to break through conventional technological issues is considered top-down technology, while technical development that aims to fabricate nanosystems from nanofunctional materials that are to be ultimately designed at the molecular level is considered bottom-up technology. Since these classifications have been discussed in past issues of "Science and Technology Trends"[10-11], this article will not go into detail, but they are completely different from the terms "top-down" and "bottom-up" as used in fields such as economics[*4].

The technical challenges for nanotech are now shifting from top-down to bottom-up technology focused on nanosystem materials development. Bottom-up technology will not bring significant benefits to industry unless it is systematized as functional materials. Both kinds of technology include characteristics of the "true nano" described in Chapter 1, but bottom-up technology carries greater expectations for radical progress and the creation of new industries because of its innovativeness and discontinuity. Accordingly, the next section will discuss Japanese competitiveness in both technologies.

Table 1 : Delphi survey results on nanotech/materials R&D levels

	Areas included in the nanotech and materials field*1	vs. US*2	vs. EU*2
Bottom-up	Nanomaterials modeling simulation	4.06	5.07
	Nanobiology	3.53	4.82
	Nano devices and sensors	4.81	5.72
	NEMS technology	4.85	5.90
	Matter and materials origination, synthesis technology, and process technology	5.58	6.31
	New materials from nanolevel structure control	5.47	6.28
	Nano measurement and analysis technology	5.15	5.94
	Environmental and energy technology	5.80	6.27
Top-down	Nano process, molding, and manufacturing technology	5.82	6.56

*1: "Nanoscience for a safe and secure society" (vs. US: 3.98) is excluded because of the difficulty of technological evaluation
*2: Indexed with equality at 5.0

Prepared by the STFC based on Reference[6]

4 Changes in the competition stages of nanotech, and Japan's strengths and weaknesses

This section considers Japan's nanotech competitiveness in top-down and bottom-up technologies as discussed in the previous section. Here, this article again addresses the results of the Delphi survey that provides a holistic overview of future science and technology. After examining the details of Japan's R&D level, the article considers venture corporations, which increase in importance every year in their roles in developing technologies and in some cases commercializing them as well.

4-1 Relationships between Japan's strengths and weaknesses as seen in the Delphi survey

Sections 2 and 3 discussed Japan's position in the nanotech and materials field as a whole by comparing it with other fields. This section addresses nine noteworthy science and technology areas in the nanotech and materials field in the Delphi survey and some of their technical issues in order to examine how experts in the field view Japan's R&D level.

Table 1 depicts assessment of the current R&D levels and rankings (5 levels) of the nine nanotech areas. Judging by area names and summaries, bottom-up technologies are listed in the upper part, with top-down technologies in the lower part. The numbers in the columns showing "vs. US" and "vs. EU" are obtained by indexing the added values of 5 levels into 10 ranks as in Figure 4. From these results, one can see that Japan is leading in top-down technology, but somewhat behind in bottom-up technology. Versus the US in particular, Japan's relative level is split in half by the equal level of 5.0.

However, there is a mixture of bottom-up and top-down technologies within some areas*5, although the percentages vary. Accordingly, this article addresses the Delphi topics for "Matter and materials origination, synthesis technology, and process technology," which is located in the middle range, displaying the evaluation results in Table 2. All the Delphi topics are assessed as technologies that are yet to be realized at present and should be or probably will be realized in the future. As in Table 1, in Table 2 the bottom-up oriented topics are in the upper part, with the top-down oriented topics in the lower part. In the Delphi survey, respondents selected for each of these Delphi topics the leading country or region from Japan, the US, EU, Asia (excluding Japan), and Other. Table 2 shows the countries or regions with the most votes. As in Table 1, Japan leads in top-down technologies, but is behind the US in bottom-up technologies, with one exception (nanotube manufacturing technology).

Although this analysis addresses topics in the area located in the middle of Table 1, topics in the remaining areas showed similar tendencies. For example, in areas with strong bottom-up elements, such as "nanomaterials modeling simulation" and "nanobiology," the US was overwhelmingly the leader rather than Japan. On the other hand, in areas with strong top-down

Table 2 : Delphi survey results on the R&D levels of Delphi topics included in the area, "Matter and materials origination, synthesis technology, and process technology"

	Technology topics included in the area "Matter and materials origination, synthesis technology, and process technology"*1	Leading country*2
Bottom-up	Technology to freely apply organic, inorganic, and metal materials at the nano level	US
	Methods for protein synthesis with optional structures through in-vitro sequence control that does not use mRNA or tRNA	US
	Manufacturing technology for nanotubes structured according to design	Japan
	Technology to freely control the structure and characteristics of surfaces and interfaces at the atomic level	US
	Technology to directly synthesize plastic from carbon dioxide gas and water, using light as an energy source	US
	Organic macromolecules with luminous surfaces for lighting	Japan
	Manufacturing technology using nano structure control for ultra-plastic ceramics	Japan
Top-down	Technology that uses gas phase coating to manufacture to manufacture tools harder than diamond	Japan

*1: Of the 11 topics in this area, the 8 showing clearly significant differences (R1 of at least 10%) in the response results are listed.
*2: Leading country is selected from Japan, US, EU, Asia (excluding Japan), and Other.

Prepared by the STFC based on Reference[6]

elements, more responses cited Japan as the leader.

With the challenges of nanotech research expected to shift towards bottom-up technology in the future, there is concern that Japan will be weakened in science and technology competitiveness in this field versus the US. In other words, Japan, which has developed some strength in today's nanotech field centering on top-down technologies, may gradually lose competitiveness as the stages of competition shift towards bottom-up technologies and nanosystem materials development.

4-2 Characteristics of nanotech venture businesses

Recently, venture businesses assume increasingly important roles in the creation of innovation based on frontier science and technology such as nanotech, ICT, and biotechnology*6. Accordingly, Tables 3(1) and 3(2) show US and Japanese nanotech venture businesses*7 listed in the "Nanotech Business Directory" compiled by Nomura Research Institute, Ltd.[12]. In both charts, US venture businesses are listed in the left column, with Japanese in the right, and the core technologies of the businesses between them in the middle. The list is arranged subjectively, with differences in technological approaches shown on the vertical axis. They are judged as top-down or bottom-up oriented in accordance with the standards used in the previous section. It is readily apparent that more US ventures are successful in commercializing bottom-up technology stages. On the other hand, there are many Japanese ventures in top-down technology stages that are extensions of conventional technologies.

From an industry-wide perspective, at present there are few major differences among them. In the future, however, as the areas of nanotech competition shift from top-down technologies to bottom-up technologies and nano-systematization, there is concern that these differences in venture businesses will greatly affect Japan-US nanotech competitiveness.

4-3 Comparison of the characteristics of top-down and bottom-up technologies, and the relative decline of Japanese competitiveness

Table 4 compares the characteristics of top-down and bottom-up technologies. Top-down technologies aim to resolve technical problems in current technologies, shifting the focus from one specific problem to another. On the other hand, because bottom-up technologies involve high technological uncertainty, the cost to search for their scientific and technical seeds can be enormous. If, however, nanotech advances as shown in Figure 5 and nano-systematization technology becomes the core of R&D, there may be little competition in the nanotech field because of the highly sophisticated nature of technology. Table 4 also analyzes both kinds of technology by R&D strategies and the existence of markets, as well as typical technologies.

Figure 6 follows the premises of Figure 5 and Table 4 in presenting a conceptual representation

Table 3(1) : Comparison of Japanese and US nanotech venture businesses

Bottom-up technologies

US nanotech ventures	Core technologies	Japanese nanotech ventures
Nanocrystals Technology NANOSYS, INC. ZIA LASER, INC.	Quantum dots	
CALIFORNIA MOLECULAR ELECTRONICS CO. NANOLAYERS	Nano molecular devices	
NANOLOGIC, INC.	New types of computer	
NANOPLEX TECHNOLOGIES, INC. NANOSPECTRA BIOSCIENCE, INC. NANOSPHERE, INC. QUANTUM DOT CORPORATION	Bio applications of nanoparticles	
NANOCHIP, INC. NANOMAGNETICS LTD. ZETTACORE, INC.	Ultrahigh-density memory	Optoware Co., Ltd.
Biophan Technologies, Inc. Broptics Communications Corp. Konarka Technologies, Inc. Quantum Polymer Technologies	New functional materials (Shield materials, polymer solar cells, conducting plastic nano-wires)	Nac Corporation
Molecular Nanosystems NANOMIX Zyvex Corporation	CNT (carbon nanotube) devices	Proton C60 Power Corporation Japan Gain the Summit Co., Ltd.
AVIVA BIOSCIENCES BIOMICRO SYSTEMS, INC.	μ-TAS (microintegration analysis systems)	Institute of Microchemical Technology Co., Ltd. Fluidware Technologies, Inc.
FLUIDIGM CORPORATION Micronics, Inc. NanoSpire NANOSTREAM		
iMEDD, INC.	Nanomembranes	Bio Nanotech Research Institute
ARRYX, INC.	fs-lasers Laser manipulation, etc.	Alnair Laboratories Corporation Cyber Laser Inc.
BIOFORCE NANOSCIENCES, INC. Cytoplex Biosciences, Inc. Excellin Life Sciences, Inc. GENICON SCIENCES CORPORATION IMAGO SCIENTIFIC INSTRUMENTS CORPORATION Intergrated Nano-Technologies Nano0sensors PICOCAL SPINELIX Triton BioSystems, Inc.	Inomu assay Probing Biosensors Biochips	Research Institute of Biomolecule Metrology Co., Ltd.
Quantum Precision Instruments Pty Ltd.	Ultra-compact sensors, MEMS sensors, etc.	Levex Corporation Photonic Science Technology, Inc.
Alinis BioSCiences, Inc. C SIXTY, INC. INSERT THERAPEUTICS, INC. NANOMED PHARMACEUTICALS, INC.	DDS (drug delivery systems)	LTT Bio-Pharma Co., Ltd. Interprotein Corp. NanoCarrier Co., Ltd.
	Artificial skin and retinas	NIDEK
NeoPhotonics OPTIVA, INC. SiWAVE, INC.	Optical IC	Photonics Lattice, Inc. dept Corporation
NanoGram Devices NANOPOWDER ENTERPRISES, INC. Nano-Tex, LLC. NTERA LTD.	Physical applications of nanoparticles	Clean Venture 21

Table 3(2) : Comparison of Japanese and US nanotech venture businesses (continued)

Top-down technologies

U.S. nanotech venture business	Core technologies	Japanese nanotech venture business
NANOMUSCLE nPOINT, INC.	Nanoactuators	Nano Control Co., Ltd. Eamex Corporation HEPHAIST SEIKO Co., Ltd.
CARBON NANOTECHNOLOGIES, INC. Eikos, Inc.	CNT manufacturing	Carbon Nanotech Research Institute NanoCarbon Research Institute Co., Ltd. Frontier Carbon Corporation
ADVANCED DIAMOND TECHNOLOGIES ATOMIC-SCALE DESIGN, INC. CHEMAT TECHNOLOGY, INC. INMAT LLC.	Nanocoating	SNT (Shiratori NanoTechnology) Co. T&K inc.
NANOINK, INC. NANONEX CORPORATION NANOOPTO CORPORATION	Nanoimprinting	MEMS CORE Co., Ltd. Itrix Corporation Device Nanotech Research Institute Nanodevice System Research Institute
ALTAIR NANOTECHNOLOGIES, INC. CIMA NANOTECH (Nano Powders Industries) Five Star Technologies, Inc. Hi-Q Materials, Inc. MATERIALS MODIFICATIONS, INC. Nano Interface Technologies, Inc. Nano Gram NanoHorizons, Inc. Nanomaterials Discovery Corp. Nanomys, Inc. NANOTECHNOLOGIES, INC. NANOVA, LLC. NANOVENTIONS, INC.	Nanoparticles and nanostructure manufacturing technology, etc.	Nihon Nanotech Co., Ltd. Millennium Gate Technology Co., Ltd.
Nanometrology LLC.	Nanomeasurement technology	Tsukuba Nanotechnology Co. Ltd. Technos International, Inc. Tokyo Instruments, Inc. Nanotex Corporation Nanophoton Corp. JASCO Corporation Wyckoff Co., Ltd.
	Nanofabrication, precision machinery fabrication technology, etc.	Adept Japan Co., Ltd. X-ray Precision, Inc. Elionix Co., Ltd. Cluster Technology Co., Ltd. Crestec Corporation Nano Corporation
	Crystal growth technology	Nitride Semiconductors Co., Ltd. Nanoteco Corporation SiXON Ltd. Oxide Corporation
Sherman & Associates, Inc.	Vacuum equipment/ Microfabrication processing equipment, etc.	R-DEC Co., Ltd. ADTEC Plasma Technology Co., Ltd. Optorun Co., Ltd. Katagiri Engineering Co., Ltd. Science Technology Co., Ltd. Nanotec Corporation Youtec Ltd. Litho Tech Japan Co., Ltd.

Prepared by the STFC based on Reference[12]

of changes in nanotech competition stages. There is concern that Japan, currently strong in top-down technologies, might gradually lose global competitiveness as the competition stages for technologies change.

Table 4 : Comparison of characteristics of top-down and bottom-up technologies

	Top-down technologies	Bottom-up technologies
R&D directions and technical characteristics	Stepwise progression towards physical limits by miniaturization Scaling down (from microlevel) Analytical	Shifting to nanosystems at molecular level Scaling up (from nanolevel) Interpretive: Large technological discontinuities
R&D strategies	Roadmap-type strategies Continuous	Non-roadmap type strategies and creation of new industries Probabilistic
R&D targets and markets	Clear (to some extent)	Uncertain and exploratory
Interrelationships	Problem proposing (for bottom-up technology)	Solution proposing (for top-down technology)
Typical technologies	• Semiconductor miniaturization technology • Nano-compound materials, etc.	• Molecular devices • Self-organization technology, etc.
Japan's competitiveness (vs. US)	High	Low

5 Innovation systems for nanotech commercialization

5-1 Construction and promotion of basic research supporting nano-systematization (towards nanotech research)

In order to develop bottom-up technologies and ultimately achieve nano-systematization, R&D on the scientific foundation that supports it is indispensable. Section 4-1 introduced some bottom-up technologies based on the results of the Delphi survey. There is concern that Japan, currently strong in top-down technologies, might lose global competitiveness in the future. In order to target improved global competitiveness in the area of nano-systematization, nanotech researchers must carry out basic R&D with a keen awareness of R&D in areas of high uncertainty.

However, it may be difficult for researchers involved in research on nano-systematization technologies to produce a large amount of articles and other forms of results[*8]. Unlike top-down technologies that enable relatively easy data collection, bottom-up technologies and future nano-systematization technologies deal with an almost infinite number of uncertainties, making it extremely difficult to carry out reproducible experiments or to verify hypotheses. In the first place, the kind of state-of-the-art measurement and analysis that can be considered nanoscience must be conducted in environments with uniform measurement conditions and parameters, so it tends to end up being only analysis or measurement. In this sense, one may say that few basic research methods have been established for bottom-up or nano-systematization technologies. This article asserts that true nanotech competitiveness in the future will be demonstrated in the areas of the molecular fabrication and systematization of nanostructures, where an uncounted number of elements are involved. From this point of view, Japan must structure and enhance its new nanoscience research method.

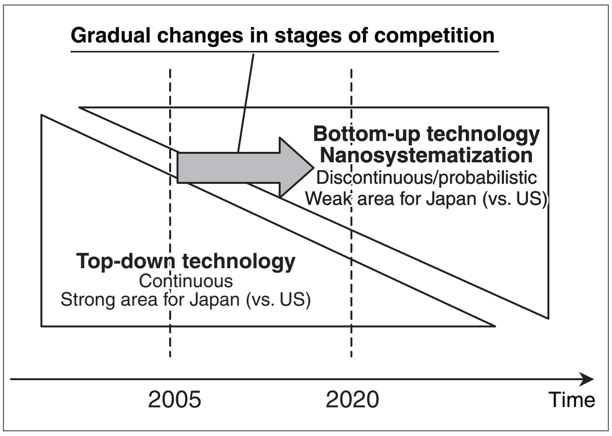

Figure 6 : Comparison of characteristics of top-down and bottom-up technologies

5-2 Construction of the nanotech venture creation system and funding functions (towards industry)

In order to create nanotech ventures, the following social and economic characteristics of nanotech must be considered.

- Inability to apply traditional categories, such as academic fields or industrial classifications, because of many transdisciplinary or interdisciplinary elements

involved in R&D
- High expectations - the potential to renovate markets or even economic society
- Extremely large ripple effects
- Geometric increase of investment from discovery/invention to commercialization of technology
- A need for continuous and incremental investment because of the difficulty of accurately determining the right investment size in advance, and because of the significance of cumulative effects
- A need for an innovation system as a supplementary system to diversify risks associated with sharply rising investment

As these characteristics show, investment in nanotech, especially its bottom-up technologies, involve high technological uncertainty, and therefore its effects are only probabilistic. Unfortunately, Japanese mechanisms for investment in state-of-the-art R&D are not as complete as those of the US. This is particularly true for investment in venture businesses. The current mainstream financing system in Japan is that a single company or a joint investment entity formed by banks, securities companies, and major manufacturers support a venture company from startup to technology development to commercialization. However, the investment amount for new businesses is smaller than that of the US, and the venture capital industry, which plays an important role in investment activities and the R&D processes, is still immature in Japan. In other words, an innovation system that can accommodate the above characteristics of nanotech, especially those of bottom-up technologies, has not established yet. The current situation in Japan is that nanotech venture businesses are reliant largely on public support, from R&D to commercialization*9. However, considering that bottom-up technologies may require more than 15 years of continuous investment to reach commercialization, public support programs alone cannot provide sufficient funding. A solution to this is a system in which a different funding source is used in every stage from startup through early, middle, and later stages. This would substantially reduce the risk to be born by each funding source and thereby restrict the total capital invested by each funding source.

5-3 Pioneering methods of creating new R&D management tools (towards management research)

Technology roadmaps, which have developed around the typical top-down R&D field of semiconductors, have played a role in securing the rationality of advance investment by clarifying the direction of investment and even predicting socioeconomic ripple effects. However, because of the following characteristics of the nanotech field, especially its bottom-up technologies, traditional methods of setting R&D strategies are no longer effective enough[18].

- Compared with the other fields (especially semiconductors), this field is lacking in structured technologies and shared recognition of future markets[19]
- Because bottom-up technologies by nature are aggregate concepts from myriad technology seeds, searching for commercially useful technology seeds is a task encompassing a broad scope and requiring enormous costs
- Because technology has a strong tendency to develop through non-linear processes, the route from investment to result is uncertain
- The advanced level and complexity of the technologies make it difficult not only to judge investment rationality in advance but also to measure the economic effects of the investment afterwards
- As technology develops, investment amounts may grow enormously and become difficult to recover
- For these reasons, investment is high risk/high return and is often underfunded

Because of these issues, study of methods for the creation of new R&D management tools is necessary. For example, the recent development of option theory is attracting attention. Since nanotech, especially its bottom-up technology, encompasses a broad range of technologies, there is a potentially ironic situation where a roadmap created through an extensive selection and concentration process is more likely to become useless depending on future trends in technology development. Maintaining the flexibility*10 of a technology roadmap towards pre- and post-roadmap events is therefore a key determinant of the future destiny of the nanotech field[20-21]. Incorporating a broad range of technology could be a great risk in conventional roadmapping methods, but the abundance of technology options available there could provide a means to hedge the risk of increased uncertainty in the future. The essence of a technology roadmap is to "visualize" options. In option theory, it is possible to see the expectations and uncertainties of advance options as ex post facto value. Conventionally, uncertainty has been something to be avoided as much as possible, but option theory shows that uncertainty also has value. The development of option theory may be able to theoretically establish results with latent potential.

Although option theory is used as an example here, it is obviously not the only possibility. At the research level, a technology roadmapping method that uses text mining is also being studied[22]. From the perspective of securing the diversity of options, Delphi surveys are attracting renewed attention because of their capacity to include many technological issues and information related to them, such as the levels of given technologies. Management researchers must therefore study new types of methods based on such policies and industry requirements. The nanotech field may soon experience the difficulty of managing state-of-the-art R&D. Establishment of new strategy creation methods in this field would be of great significance to other frontier R&D fields.

Notes

1 The Nanotechnology Network Center's "Nanotechnology literature trend survey"[3] performs keyword-based searches of nanotech-related literature. According to that report, Japan ranks third in nanotech-related articles, behind the US and China.

2 The 10 areas are nanomaterials modeling simulation; nano measurement and analysis technology; nano processing, molding, and manufacturing technology; matter and materials origination, synthesis technology, and process technology; new materials from nanolevel structure control; nano devices and sensors; NEMS technology; environment and energy materials; nanobiology; and nanoscience for a safe and secure society.

3 The term "nanosystem" is used in the US as part of the names of academic society subgroups as well as research centers of universities and research institutes. Nanosystem research is actively progressing in these research centers, a representative example of which is UCLA's California NanoSystems Institute (founded in 2000)[8]. On the other hand, the term is rarely used in Japan, but in its strategic program called "Nanosynthesis: creative monodzukuri"[9] project, the Japan Science and Technology Agency broadly analyzes research and development of "nanodevices and nanosystems" and strongly emphasizes their importance.

4 Generally, in fields such as business administration and management of technology (MOT), management that emphasizes R&D strategies or directions decided by government or organization leaders is referred to as top-down strategies or approaches, while management that emphasizes the ideas and interests of frontline researchers and activities at the individual level is referred to as bottom-up strategies or approaches. Top-down and bottom-up technologies in the nanotech field are different from this. The terms are simply used to classify the broad field of nanotech by technical approach[10-11].

5 This article addresses top-down and bottom-up technologies by a relative definition. For example, although it refers to nanomaterials simulation technology as a representative bottom-up technology, obviously both top-down and bottom-up elements constitute this technology. An example of its top-down element is the common practice of fitting the data obtained by experiments through modeling in order to elucidate physical structures unobtainable through experimentation alone. An example of its bottom-up element can be seen in attempts

to perform simulations of every behavior of molecules in order to integrate their behaviors and create nanosystems so that completely new nanofunctional materials can be designed.

6 Research to date on management of technology (MOT) has found that large companies generally tend to make negative decisions on R&D in niche technologies that involve a high degree of uncertainty regarding commercialization and that are unlikely to create a market of a reasonable scale, in fear of declines in their R&D efficiency. (See references 13 and 14, for example.) On the other hand, R&D with this kind of high uncertainty is essential for achieving disruptive innovation. From this perspective, R&D ventures that hedge risk by diversifying funding sources and maintain small-scale operating and development structures are garnering attention. (See Reference 15, for example.)

7 Reference 12 derives 77 US and 59 Japanese firms from the following materials.
US: Nanotech Venture Fair 2002 (San Diego)
Nanotech Planet Spring 2002 (San Jose)
Nanotech Venture Fair 2003 (Coronado)
Japan: Derived from "Leading cases of nanotech ventures" (management information search, summer 2002), "Japanese nanotech ventures (summary ed.)," (Nikkei Nanotechnology, August 25, 2003), "Japanese nanotech ventures (individual company ed.)," (Nikkei Nanotechnology, September 8, 2003), "FY 2004 ultraminiaturization technical development industry excavation strategy survey: Field survey of nanotech venture companies" (Ministry of Economy Trade and Industry commissioned survey), etc., and Nikkei Shimbun
Many other ventures have started since 2005; they are not included.

8 In NISTEP's research paper analysis using citation relationships[16], the bottom-up technology research area "Building of nano-structures from microstructure with microparticles and polymers" is listed as one of 133 research areas. Japan's share of the most-cited papers in this research area was about 3.7 percent, low compared to other nanotech-related areas.

9 Nomura Research Institute and many METI-commissioned surveys carry out detailed analyses of nanotech ventures. According to one of these, Reference 17, about 79 percent of nanotech venture businesses have received public R&D subsidies. Moreover, their applications for subsidies have been accepted at an astonishing rate of 88 percent. Nevertheless, about 55 percent of nanotech ventures operate at a loss.

10 For example, current technology roadmaps are updated to meet changes that were unpredictable at the time of formulation, through annual revisions after the fact. In the future, however, management tools that can even visualize technologies outside the roadmap (off-road technologies) as options need to be developed.

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Daisuke KANAMA, PhD
Nanotechnology and Materials Research Unit, Science and Technology Foresight Center

Interested in the relationships among scientific technology, economic society, and innovation. His research focuses particularly on the role of universities and public research institutions and the importance of publicness in national innovation systems. Also interested in and carries out research on research trends in the nanotechnology field

Akio KONDO, PhD
1st Theory-Oriented Research Group

Engaged in economic analysis of science and technology-oriented industries such as semiconductors. Interested in exploring the proper form of policy for building national and regional innovation systems effective for strengthening industrial competitiveness based on science and technology and for creating new industries.

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