Center Director's Vision

International Center for Materials Nanoarchitectonics (MANA)

Prospective Center Director:
Masakazu Aono
Fellow
Coordinating Director, Key Nanotechnologies Field
Managing Director, NanoSystem Functionality Center
National Institute for Materials Science (NIMS)

As the prospective director requested to setup a research center supported by the World Premier International Research Center (WPI) Initiative of MEXT, I will describe my enthusiasm toward the establishment of this research center and research vision which is the basis of this enthusiasm.

1 Introduction

1.1 Materials are the mother of science and technology

This title expresses what I have always felt during my 35 years of research. I would like to explain how I acquired this feeling by describing two of my research projects: the first project in which I was engaged in as a researcher and my current ongoing project.

Approximately 35 years ago, electron emission materials with excellent properties were required for the development of electron microscopes and electron-beam lithography machines. At that time, people knew of the existence of a promising candidate material, lanthanum hexaboride (LaB_6), which has an extremely low work function (2.3 eV), although the cause of such an extremely low work function was unclear. I was successful in elucidating the cause (explained later); this success was only possible because I was working at the National Institute for Research in Inorganic

Materials (NIRIM), the predecessor of the National Institute for Materials Science (NIMS). At NIRIM, it was possible to grow single crystals of LaB_6, the melting point of which is extremely high (2700°C), by the floating zone method 30 years ago. I analyzed the surface structure (atomic arrangement) of a grown single crystal of LaB_6 utilizing two new measurement instruments constructed by myself, namely, the angle-resolved X-ray and UV photoelectron spectrometer and the impact-collision ion scattering spectrometer. The results revealed that the (001) surface of LaB_6 is covered by La ions, leading to an extremely low work function. On the basis of this discovery, we developed an electron emission device with a tip made of the (001) surface of a LaB_6 single crystal with Denka Corporation. This device is now indispensable in various devices using electron beams, including electron microscopes and electron-beam lithography machines. Through this series of research, which was my first as a researcher, I developed the strong impression that a new technology is born from a new material or materials.

I would like to introduce another recent example from my ongoing research. I invented (discovered) an “atomic switch” several years ago. It was indeed a serendipitous discovery. Since I organized/managed the Aono Atomcraft Project of the Exploratory Research for Advanced Technology (ERATO) program sponsored by JST in 1989, it has been one of my interests to fabricate nanoelectronic circuits using atomic chains. I therefore tried to create a conductive path by supplying silver atoms one by one along a given line on a sample surface with the use of the scanning tunneling microscope (STM). For this purpose, we prepared a STM tip made of silver sulfide (Ag_2S) that is a typical solid electrolyte so that silver atoms in it are moving freely, and the tip was scanned on a sample surface, an appropriate voltage being applied. As expected, silver atoms were supplied to the sample surface from the tip and a conductive path was formed along the scan line, but we came across a more important phenomenon. Under a certain applied voltage, silver atoms precipitated at the apex of the silver sulfide tip and created a bridge between the tip and the sample. Furthermore, when the applied voltage was reversed, the silver atoms redissolved into the silver sulfide tip, and the bridge disappeared. We had realized a new nanoscale switch. We decided to call this switch an “atomic switch”. In subsequent research, we found that this switch has many excellent properties exceeding our predictions. NEC Corporation, with which we are conducting joint research, has begun studies on manufacturing next-generation programmable logic operation devices that incorporate atomic switches. Incidentally, the development of recently available new memory devices such as resistive RAM and redox RAM, was triggered by the development of our atomic switch. Through the research concerning this atomic switch, I renewed my conviction that a new technology is created through the development of a new material or materials.

I have consumed much space in describing my own research experiences, but as exemplified by Edison’s light bulb being realized 100 years ago by the use of bamboo from Kyoto, by the information technology of the past 50 years being founded on silicon, by the recent blue diode being realized using gallium nitride, and by fertilizer and agricultural chemicals playing a decisive role in the marked increase in food production, it is a universal fact that new materials bring about new technologies. Although this fact is not well recognized, it can be the proof that new materials for technology are as important as air to us.

1.2 21st century as century of technology and new materials development

The 20th century is said to be the century of science. Indeed, there have been three major developments in the last century: the discovery of the theory of relativity, the establishment of quantum mechanics, and the discovery of DNA. These developments are closely related to our life today in terms of atomic energy, communications technology, and gene therapy. Remarkable scientific developments are expected to continue even in the 21st century (in particular, much progress is expected in the field of brain science); however, I believe that the prediction that the 21st century will be the century of technology will be realized. Technological developments tend to be considered less important than scientific developments. However, the situation of technology in the 21st century will be substantially different from that in the 20th century; technologies in the 21st century will be highly advanced so that it will change not only our life but also our philosophy. As a good example, if mankind can send men to Mars, our philosophy will be affected and change, and such a change will be brought about by technology rather than science.

Technology that brings about numerous benefits and welfare to mankind is also causing serious problems, as represented by global environmental pollution. Also, the rapid and global expansion of industry supported by technology is creating a new crisis of the depletion of natural resources and energy. Thus, the 21st century is a century in which we humans will actually be brought face to face with the limitations of the earth for the first time; the future of mankind depends on whether we can find a path of sustainable growth under the severe restrictions related to energy, environment and resources. These serious problems resulting from the progress in technology must be resolved, not by abandoning technologies but by further advancing the technologies currently available. Japan, which has a national policy of being a world leader in science and technology is obligated to address this issue.

However, the demand for new materials in realizing such advanced new technologies is at a very high level. The reason behind the use of silicon in solar cells is that it is a nice semiconductor; however, such a single function will not be sufficient in the future. Materials with multiple properties, such as those similar to silicon (or those with superior functionality compared with silicon) but require less energy for their production, will be needed. Currently, it is considered a matter of course to cool superconductors used for superconducting magnetic levitation trains to a ultra-low temperature. However, room temperature superconductors will be required in the future.

In the development of nanoelectronics for realizing a ubiquitous information technology society by reforming communication technologies, the development of devices operating on the basis of a completely different principle from that of today's silicon-based CMOS devices is necessary; the development of materials required for these devices will be fairly sophisticated and diversified. The development of new materials that respond to the high level of demand cannot be realized if we maintain the conventional materials development paradigms adopted thus far. It is necessary to adopt a new materials development paradigm.

2 Goal of Research Center

2.1 New paradigm for materials development and nanoarchitectonics

How can we set a paradigm for new materials development? The marked development of nanotechnology and nanoscience during the past 20-odd years has provided us with half of the answer. Regardless of the type of product, such as macroscopic structural materials or microscopic electronic device materials, or the types of inorganic materials, organic materials, and biomaterials, interesting and diversified functions that had previously been unavailable have been added to materials through the control of their structures at the nanoscale. This has been proven by many examples. Such nanoscale structural control will be an unshakable pillar in materials development in the new paradigm.

The marked development of nanotechnology has given great confidence to researchers engaged in materials development, and has built up their hopes of realizing dreamy developments in the extension of current nanotechnology. However, doubt as to whether nanotechnology has made the expected progresses has recently been cast. This reflects the recent recognition of materials researchers that some breakthrough is necessary for nanotechnology to break out of the shell of nanoscience to become a truly practical technology. That is, some essential element is missing.

Nanoscience and nanotechnology have been developed as a science or technology in local nanoscale space locally. Demonstrations that have surprised material scientists have been presented one after another; however, these concerned only a small number of atoms or molecules in limited spaces at the nanoscale. For example, demonstrations of materials creation and fabrication, such as arranging atoms or molecules in a desired manner by manipulating them individually, rearranging atoms and molecules locally under an equilibrium condition into a different arrangement, and fabricating conducting polymer chains at an arbitrary location by inducing chain polymerization reactions via the stimulation of a single molecule, for example, were performed for a limited number of atoms and molecules located in a limited space. Also, demonstrations of the extraordinary high conductivity of carbon nanotubes, the operating characteristics of various single-electron transistors (SET), and the functions of single-molecule transistors, for example, have also been realized for a single molecule or structure. However, for practical applications, the scaling up or improvement of the creation and fabrication methods and the organic integration and mutual linking of individual functional molecules and structures are required. This is essential to create novel functionality of practical use as a whole. As an analogy, although individual cells in biological bodies have excellent functions, a more important fact is that these cells are organized and exhibit a function as a whole.

In short, a new technology system, in which we can arrange individual nanostructures that have useful functions into a desired arrangement, is required. We call this technological system "nanoarchitectonics*", and explore it at this research center.

Nanoarchitectonics can be classified into two major areas: "NanoMaterials Creation" and "NanoSystems Organization" (refer to Fig. 1). As a simple example of NanoMaterial Creation, the creation of a new material that cannot exist in nature has already been accomplished by compositing a material with single nanosheets obtained by chemical exfoliation from a different layered material. It will be possible to create new interesting materials with new functions by advancing a similar method. A simple example of NanoSystems Organization is the construction of a nanoelectronics circuit. Interesting electronics devices made of carbon nanotubes and functional molecules have been experimentally fabricated as single devices; however, they cannot be put to practical use unless these devices are integrated and mutually linked into one system.

At this research center, we will realize nanoarchitectonics through the development of new various technologies in four areas: 1) Atom/Molecule Novel Manipulation, 2) Chemical NanoManipulation, 3) Field-induced Material Control, and 4) "Artificial" Self-organization ("artificial" means "controlled" or "guided"). Their contents are shown in Fig. 2 using examples (all of these examples are selected from the world's first research of their kind performed at NIMS).

In Atom/Molecule Novel Manipulation, the basic approach is the control of the arrangement and bonding state of individual atoms and molecules using the proximity

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*** Note**

The word "nanoarchitectonics" in this context was used for the first time in the world at the First International Symposium on Nanoarchitectonics Using Suprainteractions (NASI-1) for which I served as chairman. The second symposium, NASI-2, was held in Los Angeles and chaired by Prof. Jim Gimzewski of UCLA (one of the principal investigators of this research center), and the third symposium NASI-3 is scheduled to be held in Cambridge and will be chaired by Prof. Mark Welland of Cambridge University (also one of the chief researchers of this research center). "Suprainteraction" in the symposium name is also a coined term by us meaning long-range interaction. This is also another important concept in this research project.

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probe (tip) of a scanning tunneling microscope (STM) or an atomic force microscope (AFM). This method is unique in the sense that individual atoms and molecules can be manipulated, and cannot be replaced with any other method; however, it is disadvantageous because much time is required to manipulate a large number of atoms and molecules. Our approach is to aggressively overcome this disadvantage and advantage of the excellent property of this method rather than abandoning it. The disadvantage can be overcome by superparallel driving of multiple probes by computer

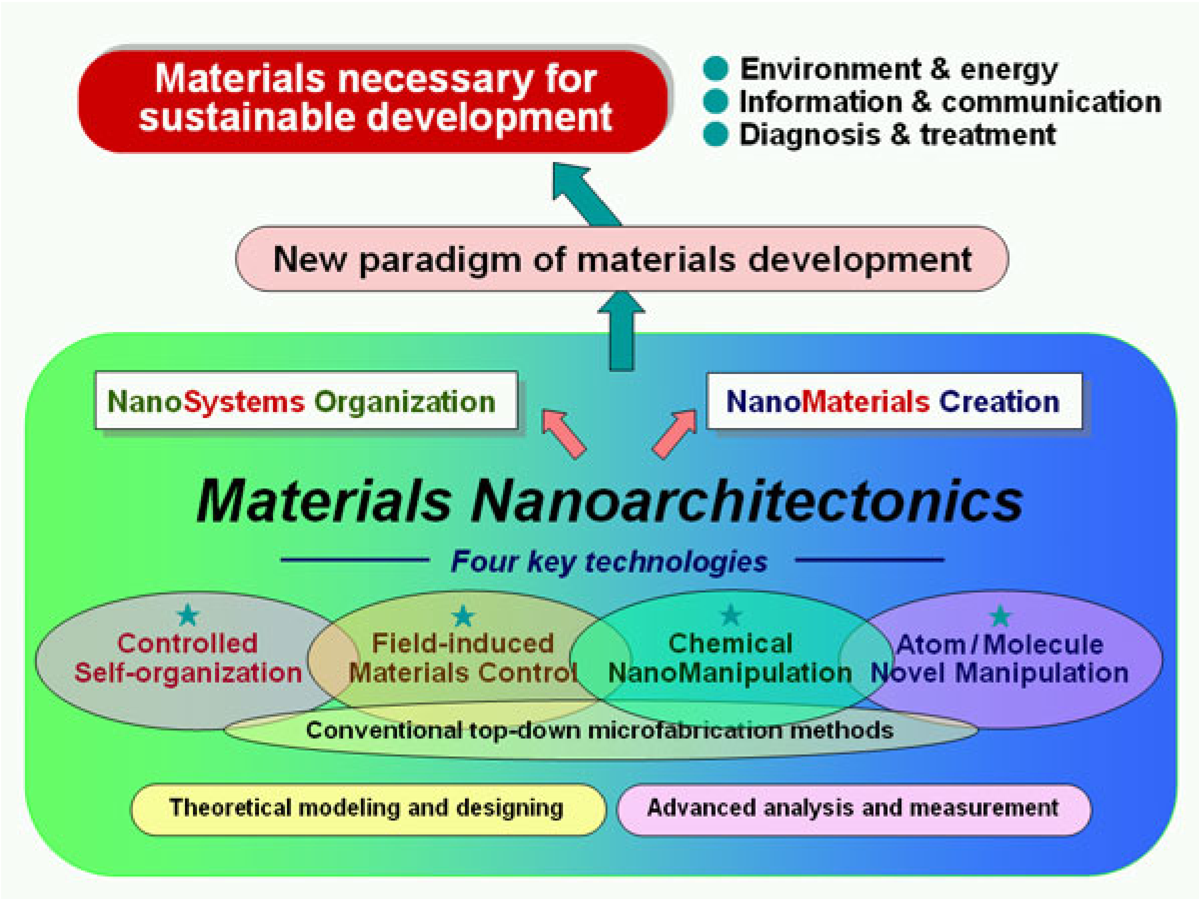

Fig. 1 New paradigm in materials development through material “nanoarchitectonics

control and controlling self-organization of atoms and molecules on a resulting template. In Chemical NanoManipulation, nanoscale materials and structures can be constructed by skillfully and differentially using the chemical equilibrium and inequilibrium states in a liquid or solid phase in time and space. Nanomaterials and various nanostructures can be constructed more efficiently than by the atom/molecule novel manipulation method. In Field-induced Material Control, we exploit the state change of materials under the presence of electric field, magnetic field, electromagnetic field (light and X-ray), strain field, electron flux and ion flux. Although this method has previously been employed even until now, we will aggressively develop new untried approaches at this research center. For example, it has been clarified in a recent study that after molecules, which have been adsorbed onto a substrate, are arranged in a desired pattern using a scanning probe, their positions can be fixed by irradiating X-rays that have a wavelength specific to the molecule of concern. Furthermore, the possibility of controlling the crystal orientation of nonmagnetic nanoparticles using a magnetic field has been demonstrated. In “Artificial” Self-organization, we will adopt the conventional self-organization method of mutual interaction that molecules (or atoms) possess, but add “artificial” modifications. There are two types of modifications. One is the control of self-organization using external fields (including the application of a local field and the use of a template), and the other is the modification of structures formed by self-organization with the use of subsequent skillful fabrication methods. As demonstrated by some of the examples described above, it is important to fuse the various technologies of the four areas.

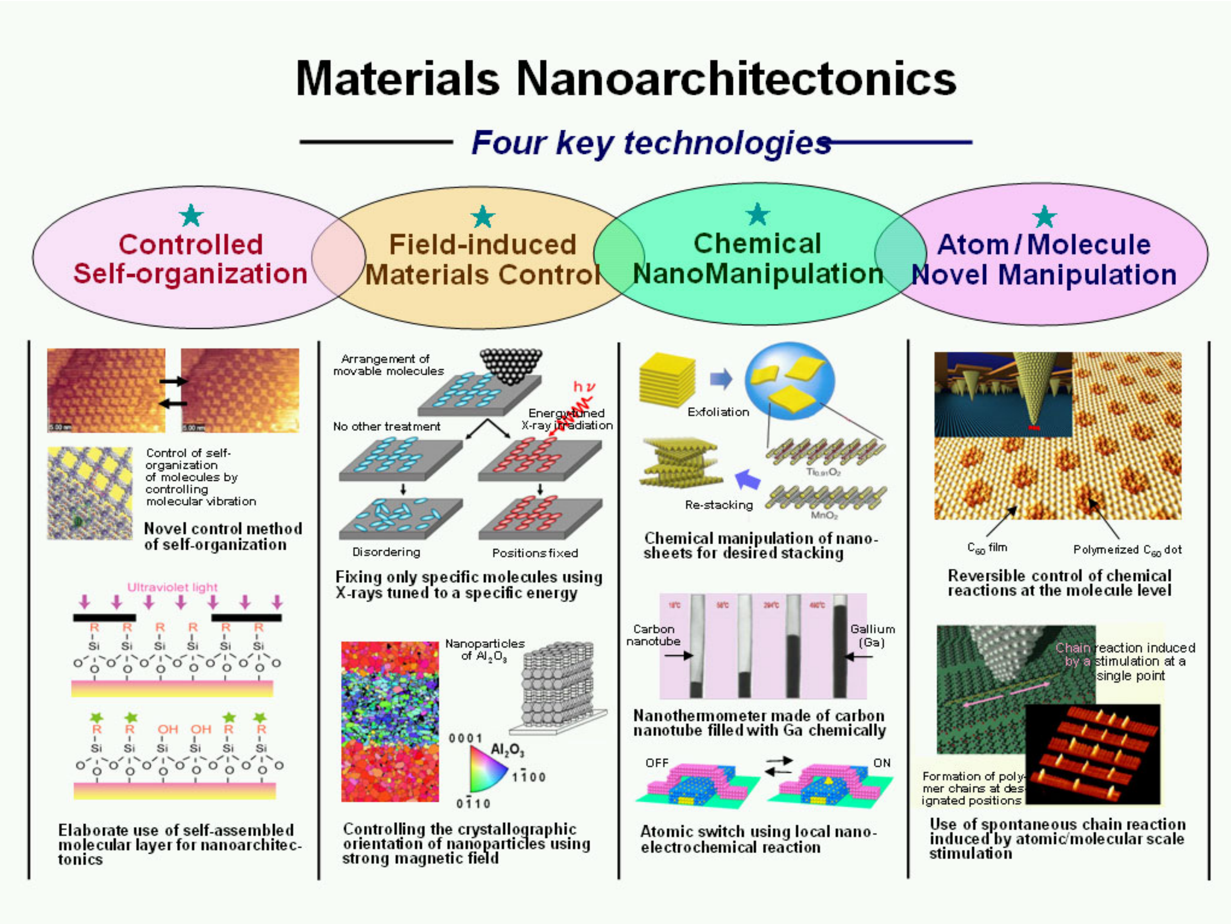

Fig. 2 Illustration of materials “nanoarchitectonics”

We will explore new paradigms for materials research on the basis of nanoarchitectonics, which is based on the above-described technological development, and create innovative materials that will enable the development of the new technologies required for sustainable growth in the 21st century.

2.2 Outstanding feature of NIMS as host organization

It is important not only to develop but also to combine individual technologies in order to achieve concrete results in the development of new materials through the integrated development of the above-described new technologies in nanoarchitectonics. Therefore, the organization responsible for such a task must be one that is exclusively dedicated to materials research and that has talented personel, experience, and facilities that exceed a certain level. In this sense, NIMS is a highly suitable organization as the host institute of the research center. In fact, NIMS boasts numerous outstanding achievements such as (1) the first successful fabrication of diamond thin films by chemical vapor deposition, (2) the ultrahigh-pressure synthesis of single-crystal diamond, (3) the discovery and structural identification of bismuth oxide high-temperature superconductors, (4) the growth of single-crystal dielectrics of the world's largest size and highest quality, (5) the basic research and practical use of an excellent electron emission material of single-crystal lanthanum hexaboride (mentioned previously), (6) the development of various super-heat-resistant alloys, the development of "super steel", which is unparalleled by any other in the world, and (7) the development and practical use of coiled wire fabrication technology of high-temperature superconducting materials. Here, this tradition is being continued with recent eminent results, such as (8) the discovery of the cobalt oxide superconductor, (9) the development of superhigh-speed plastic ceramic, and (10) the production of the superconducting diamond. In the area of materials development in the nanoscale region, NIMS has a distinguished track record, including (11) experience in the construction of various nanostructures by means of manipulating atoms and molecules since the inauguration of the Aono Atomcraft Project under the ERATO program organized 18 years ago (discussed previously), (12) the discovery and application of atomic switches resulting from atomic and molecular manipulation (discussed previously), (13) the formation of conductive polymer chains at desired locations by chain polymerization, (14) the development of memory with bit density greater than 100 Tb/in^2 by using C_{60} molecules, (15) the development of a nanothermometer using carbon nanotubes, (16) the discovery and use of metal oxide nanosheets with useful functions, and (17) the realization of semiconductor quantum dots, of which even the internal structure is controlled, by droplet epitaxy. Also, in the area of nanoscale measurement technologies, achievements include (18) the development and use of multiprobe STM (nanotesters) with 2, 3, and 4 multitips, (19) the development and use of a new technology for analyzing the nanostructure and electron state, as well as the spin state, of light emitted from an STM by spectroscopy and polarization analysis, and (20) the development and use of STM operated at ultralow temperatures, in strong magnetic field, and in ultrahigh-vacuum. In addition to the above, NIMS operates many large-scale facilities, such as (21) the world's strongest magnetic field generator, (22) the world's highest-frequency nuclear magnetic resonance (NMR) spectrometer using the strong magnetic field generator, (23) an ultrahigh-pressure generator that can be used even for the fabrication of artificial diamond, (24) an exclusive beamline at the synchrotron radiation facility (SPring-8), and (25) a high-current metal ion beam generator.

It is necessary to promote research at the research center by recruiting talented researchers from all over the world by opening our door to the world (open environment; this is one of the major goals of the World Premier International Research Center (WPI) initiative of MEXT). To this end, experience in internationalization, such as the use of English as the official language, is required. NIMS has an ample track record in this area. Through the five-year management experience since the inauguration of the International Center for Young Scientists (ICYS), we have accumulated a great variety of experience related to international matters by using English as the official language (in both research activity and administrative work), by organizing multinational groups of young researchers, and by appointing internationally prominent researcher advisers. Moreover, NIMS holds a student summer school every year in cooperation with Cambridge University and the University of California, with special emphasis on international exchange among young researchers.

NIMS with its excellent environment in both research and management, is no doubt the appropriate organization to handle the formation of a research center for the WPI initiative.

2.3 Fostering young research leaders

Cognizant that the mission of the WPI initiative is the establishment of a world-class research center, I would like to emphasize the importance of fostering young researchers, particularly young research leaders, at this type of research center. It may not be necessary to mention that in many cases, research is advanced by the originality of young researchers. When the current status of science and technology in Japan is viewed from this perspective, the fostering of young researchers (which include students, postdoctoral fellows and young research leaders) is not necessarily systematized. In many universities, students are not taught how to write scientific papers in English. Postdoctoral fellows, in many cases, carry out subcontract-type research for their superiors. Young research leaders, such as research associates in universities and group leaders in research organizations, are busy with menial chores. Another recent phenomenon is that young researchers in Japan have no desire to go out of Japan to acquire international experience. It is timely that the WPI initiative promotes the formation of an environment in which postdoctoral fellows and senior researchers can devote themselves to research and internationalization. If this is the goal of the WPI initiative, I believe that an additional step should be taken including the fostering of young researchers (successors, from a person of my age) as another goal of this project. I think this is extremely important for the development of Japan's science and technology. NIMS has been putting special emphasis on fostering young researchers and on internationalization. The operation of the International Center for Young Scientists (ICYS), the holding of student summer schools in cooperation with Cambridge University and the University of California (I am in charge of the summer school with Cambridge University and will visit the university with approximately 20 students this summer), and the holding of closed mini seminars with Novel laureates (Dr. H. Rohrer and Prof. H. Kroto) are some typical examples of our activities.

From the viewpoint of fostering young researchers, at this research center, we will not only carry out the world's top-level research but also enrich student education by incorporating the Graduate School of Material Science of the University of Tsukuba, which is operated by NIMS, as well as plan to adopt a mentor system in which principal investigators nurture young research leaders. Furthermore, we hope that young researchers will learn cooperation with industry to realize the practical applications of their research accomplishments. To this end, we plan to use our Platform, that is, cooperative research operated by NIMS in association with companies and the Evening Seminars (held every week) that are open to researchers from industry.

3 Conclusion

Finally, Japan, which has a national policy of being a world leader in science and technology, is obligated to address the serious issue that technology, which on the one hand, provides us with benefits and welfare, but on the other hand, also causes global-scale environmental destruction. Japan should lead in exploring a path towards sustainable growth. To this end, the development of various new technologies related to environment, energy, resources, information and communication (in reality, more than half of the energy used by advanced countries is for information and communications), and medical treatment is necessary, and the development of innovative materials required in such technologies is of extreme importance. To respond to such needs, we will establish a new paradigm for materials development on the basis of nanoarchitectonics, develop innovative materials and offer them to the world.

To accomplish the above, we will form this research center by inviting excellent researchers from the world over under NIMS as the host organization. The participation of principal investigators from UCLA, Cambridge University, Georgia Institute of Technology, CNRS in France, Tsukuba University and Tokyo University of Science has been confirmed.

Finally, I am sincerely grateful to Dr. Heinrich Rohrer, who was awarded the Nobel Prize for Physics in 1986 for his contribution to the invention of the scanning tunneling microscope (STM), and whom I highly respect, for offering to write a recommendation for me as the prospective center director.

（Host institution： National Institute for Materials Science
Title of Center Project International Center for Materials Nanoarchitectonics）