Nanotechnology

Toward innovation and
a society of sustainable development

Nanotechnology at AIST

Toward innovation and a society of sustainable development

New developments in nanotechnology research

To the global development in nanotechnology research have been added the social acceptance and standardization of nanotechnology, and a large trend encompassing these aspects is in the process of taking shape. In Japan as well, the Third Science and Technology Basic Plan in line with these trends started as of this fiscal year. In the Plan, nanotechnology/materials research area is clearly recognized as a priority field to be promoted, showing the increasing anticipation for its contribution to industrial technology.

Research strategies and nanotechnology

To achieve the Second Medium Term Plan, AIST formulated research strategies which respond to the diverse expectations of society through limited research resources, and disclosed the future directions of its research. Nanotechnology research at AIST is mainly implemented in the area of nanotechnology/materials/manufacturing. The core concept of research strategies in this area is “minimal manufacturing,” which works to construct “a technological and cyclic system which generates the maximum function through use of minimal resources and input of minimal energy (production cost/environmental load), and which also controls wastes to a minimum.” In the concept, nanotechnology plays a key role as a leading-edge technology. Nanotechnology research at AIST is not limited to the research area mentioned above, but also contributes as an important basic technology to the fields of life sciences, information and communications/electronics, and environment/energy.

World-leading efforts at AIST

AIST has been leading programs such as the Nanotechnology Program of the Ministry of Economy, Trade and Industry, carrying on from the outcomes of our world-pioneering Atom Technology Project. Presently, many projects within this Program are in their final stages. AIST also participates in many undertakings of the Nanotech Research and Development of Nanodevices for Practical Utilization of Nanotechnology project kicked off in 2005, as the central research institution.

Needless to say, nanotechnology is a basic technology that breaks new ground for science and technology, and is also relevant to many existing industrial technologies, extending their reach or depth, and is thus expected to prove useful in resolving various issues of today’s society. Meanwhile, there is a concern over the possibility of unexpected negative results being yielded, as the objects of our research become nanomaterials and such of a size domain which has been hitherto unventured. AIST is thus actively engaged in research from a risk control perspective, in order to foster the healthy development of nanotechnology. We have started research on methods for safety testing of nanoparticles as of FY 2005, targeting future international standardization.

In closing, we hope that this pamphlet offers the readers some understanding of AIST’s nanotechnology-related efforts.

Research Coordinator
Kazuo Igarashi

Figure. From Atom Technology Project to Nanotechnology Research at AIST

Catch a glimpse of nanotechnology R&D in the world

Technology Information Department
Mizuki Sekiya, Junko Takahashi, Kouichi Miyamoto, Shigeyuki Sekine

What is happening in the nanotechnology research and development now? In this short column, we briefly introduce research trend of nanotechnology in the U.S., Europe and Asia.

USA

The U.S. is strategically advancing research and development in nanotechnology (NT) led by the National Nanotechnology Initiative (NNI), a comprehensive NT research and development framework. US maintains its position as the global leader in NT, showing dramatic increase in related patents as well as investment which accounts for about a quarter of the global total. Meanwhile, the U.S. is concerned over the tight competition in research and development with Japan and Europe, as well as its narrowing lead against countries such as South Korea and China. The NNI strategic plan for 2006-2010, announced in 2004, sets forth its policies that further strengthen research and development, human resource development and industrialization of NT for maintaining competitiveness of the nation.

Based upon such a situation, the total budget of NNI, despite the tight financing policy of the Bush administration, is 1.275 billion dollars (request for FY2007), which is more than twice the figure at the time of NNI's launch.

It attracts a great deal of interest that how to balance research and development of NT applications with research on environment, health and safety (EHS) implications as one of the investment issues facing NNI. There have been some cases where safety-related research is implemented even in programs which are not included in the budget category of research on EHS, reflecting increasing concerns over the safety of nanomaterials.

In reflection of current situation, the Green Nanotechnology Initiative led by the U.S. Environmental Protection Agency attracts attention as it focuses on the research and development of eco-friendly and less stressful on human health technologies using NT.

Europe

In May 2004, EU published "Towards a European Strategy for Nanotechnology" in which it identified the issues to be faced in order for EU to lead the world in NT. Among these, returning the outcomes of research and development to society through industrialization was recognized as a priority. In response, in June 2005, "Nanosciences and nanotechnologies: An action plan for Europe 2005-2009" was announced, indicating the action plans for Europe to lead the world in R&D and innovations in nanoscience/NT.

In the EU summit meeting held on March 24, 2006, the new Lisbon Strategy which aims for economic growth and job creation was adopted. It targets raising the present research and development investment, which is sum of public funds and corporate spendings, from current level of 1.9% to 3% of GDP in the EU, by the year 2010. In addition, the founding of the European Institute of Technology (EIT), to be responsible for the promotion of development across EU of leading-edge technologies such as NT environmental technologies, was agreed upon.

In January 2006, EU's Sixth Framework Programme (FP6, 2002-2006) announced the nanoscience/NT roadmap for up to year 2015, and FP7 (2007-2013, 50.5 billion euros in 7 years) stipulates that "Knowledge is Europe's best resource." NT-related topics listed in FP7 include nanoelectronics, integrated microsystems/nanosystems and downsized integration as the essential technologies for "Nanosciences, Nanotechnologies, Materials and New Production Technologies" (3.4 billion euros) and "Information and Communication Technology" (9.1 billion euros).

In the UK, keeping a distance from EU, the Department of Trade and Industry announced in 2004 the Science and Innovation Investment Framework 2004-2014, in which the budget plan (2005-2007) identifies NT as a basic technology to underpin other fields.

Asia

In Asia, NT research and development as well as fostering NT industries are implemented distinctively per region, and Japanese cooperation is anticipated. AIST sponsors the Asia Nano Forum in which it establishes networks and holds international conferences to allow relevant parties to discuss standardization, societal implications, and human resources development in NT.

In China, research bases are established in the Chinese Academy of Sciences and Peking University, etc., where substantial national funds are being invested. In addition, NT bases have been established in Beijing and Shanghai for promoting NT spin-offs new businesses and technology transfers.

South Korea established a 10-year plan to promote NT in 2001, investing heavily in research and development. Although patenting and new businesses in NT are showing rapid growth, basic research and bio fields are considered still rather weak.

Taiwan launched a 6 year plan in 2003. In addition to research and development and fostering industry, it is also enthusiastically tackling the issues of human resources development and societal implications of NT.

India kicked off a nanotechnology initiative in 2001, which promotes priority support for research and development, strengthening of infrastructure, human resources development, and coordination between industry and academia.

Singapore promotes research and development that is beneficial to existing industries, focusing on electronics, science, bio and medicine.

In Australia, the Commonwealth Scientific and Industrial Research Organization (CSIRO) is focusing on materials and bio within NT.

Potential of bottom-up nanotechnology

The limit to top-down product fabrication?

Moore's Law was proposed in 1965 by Gordon Moore, co-founder of Intel Corporation, regarding the miniaturization trend in semiconductor chips. Stating that "the number of transistors integrated on a chip doubles every two years," it beautifully characterized the progress of semiconductor microfabrication technology over the following 40 years. Presently, the size of mass production level transistors has reached the neighborhood of 50 nm, already plunging into the nanotechnology realm. Moore's Law is believed to hold for a while yet to come.

How far will top-down type technologies, in which materials are processed to fabricate microscopic objects, continue to make progress in the future? Although processing precision is expected to reach 20 nm within the next 10 years, high technical and economic hurdles are expected to be encountered in its practical application. The cost for new construction of a sophisticated semiconductor production line is as high as several hundred billion yen. The economic hurdles which are anticipated to expend the investment capacity of corporations to an extensive degree pose difficult structural issues – not limited to semiconductors, but also applicable to liquid crystal displays and such – which are common to other leading-edge technology industries.

The potential of bottom-up nanotechnology

Nanotechnology embodies two potential directions for development. The first is the increasingly radical direction of rushing ahead to the bitter end in the road of top-down technology which it has followed up to present, and the other is the road of fundamentally resolving the issues encompassed in the former, or in other words, the direction headed for bottom-up type technologies. The technology for spontaneously building a structure comparable in complexity to a semiconductor chip, based upon the chemical bonding and intermolecular forces intrinsic to atoms and molecules and without depending upon the artificial manipulation of processing, is what we call bottom-up nanotechnology.

The ideal form of bottom-up technology would be for the target objects, be them transistors or PCs, to come into being naturally, upon our simply mixing the required materials together, much as living organisms synthesize protein and lipid molecules from DNA to autonomously create cells and organs. It constitutes the ultimate on-demand technology which requires no large industrial plant, but in which the required objects are cumulated at the required position at the required time. Furthermore, it is not executed by someone looking at a blueprint, but by the substances themselves, autonomously and in parallel in various places.

While this ideal may yet be a distant dream, the natural world is utterly full of such bottom-up activities, beginning with living organisms. Bottom-up nanotechnology, which understands and imitates nature's laws of creation, is anticipated to play a leading role in a sustainable society. As it seeks miniaturization and higher performance while at the same time realizing the ultimate in resource and energy conservation, it is even capable of detouring around the economic hurdles of top-down type technologies.

The minimal manufacturing for which AIST's nanotechnology aims is precisely the realization of such a technology.

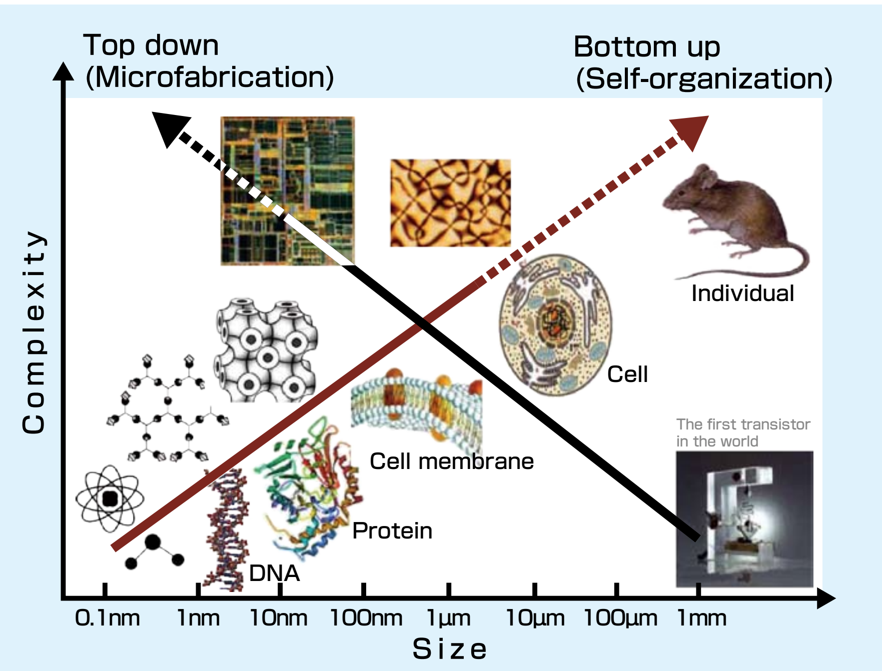


Figure. Limits to top-down product fabrication, and the potential of bottom-up nanotechnology

Nanotechnology Research Institute
Hiroshi Yokoyama

Synthesis and nanobio applications of organic nanotubes

From microchips to nanochips

The degree of integration of computer chips is increasing steadily every year, owing to progress in semiconductor microfabrication technologies.

Likewise, miniaturization advances in the separators and devices with hollow cylinder constructions indispensable to separation analysis of chemical substances. Recently, high-sensitivity analysis at a femtomole level (a level of 10^8-10^{10} converted to number of molecules) has become possible using a microchip having a channel structure of diameter approximately 100 μm (Figure, left).

However, it is extremely difficult to prepare a space to confine just one molecule inside for ultramicroanalysis. Thus the miniaturization and integration of analytical devices requires technological reform from a completely different perspective.

Utilizing the self-assembly of molecules

We are working on development of hollow cylinder structures (organic nanotubes) which exploit the phenomenon where amphiphilic molecules possessing both hydrophilic and hydrophobic groups in a single molecule spontaneously aggregate in water (molecular self-assembly).

Recently, we succeeded in achieving mass production of organic nanotubes using solvents in the amount of only one thousandth or less compared to the conventional amounts required for molecular self-assembly. In addition, we designed and synthesized a new “wedge-shaped lipid molecule” possessing two hydrophilic groups of different size (Figure, right top). Through molecular self-assembly in water, we are able to create nanotubes of either of the two distinct diameters of approximately 20 nm and 80 nm.

Results of in-depth structure analysis on this nanotube reveal that it is an organic nanochannel possessing asymmetric inner and outer surfaces, of hydroxyl groups covering the outside surface and amino groups covering the inside surface.

Further, we partially imparted a positive charge to the amino groups of the organic nanotube in aqueous solution, and successfully demonstrated for the first time in the world that we could encapsulate spherical proteins (diameter 12 nm) and polymeric nanoparticles (diameter 20 nm) possessing negative charge within the hollow cylinder (Figure, right bottom).

As described above, we are advancing research utilizing molecular bottom-up technologies, on miniaturization and integration of analytical devices using hollow cylinder structures of 10-100 nm, as well as their nanobio applications utilizing encapsulation, separation, sustained-release and sensing functions.

Nanoarchitectonics Research Center
Toshimi Shimizu

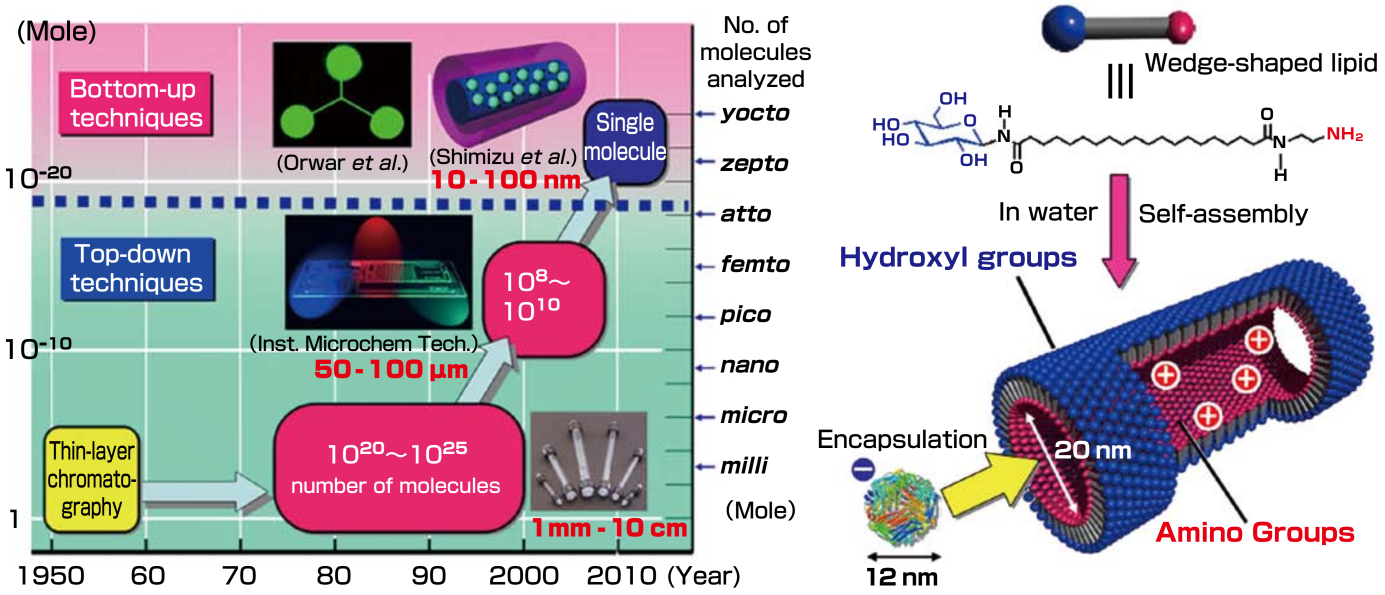


Figure. Chronological transition of miniaturization of hollow cylinder spaces, and the organic nanochannel consisting of molecules

New developments in synthesis technology of carbon nanotubes

AIST, led by its Research Center for Advanced Carbon Materials, is working to develop synthesis technologies targeting industrial application of the carbon nanotube.

Direct injection pyrolytic synthesis method

Single-walled carbon nanotubes (SWNTs) supplied by conventional mass production techniques do not satisfy the requisites as industrial materials in terms of quality, and thus require post-treatment such as purification or modification on the part of the users.

By precisely controlling the reaction conditions in the direct injection pyrolytic synthesis method (DIPS method), a synthesis method of SWNT, we have succeeded in developing a synthesis technique showing dramatically improved purity and crystallinity (graphitization) of the product, reduced impurity concentration and structural defects at a tenth or lower compared to conventional mass production techniques, as well as a catalytic efficiency of roughly 100-fold.

Use of this high-quality SWNT enables us to spin high-strength fiber SWNT wires as well as prepare mesh sheets of SWNT (Photo 1) for cell culture purposes, without use of surface treatment or binders. Furthermore, in addition to the quality (purity and graphitization) being improved dramatically, the SWNT diameter can be controlled with a precision to the 0.1nm level.

Supergrowth technology

We have discovered a completely novel growth mode (we call it supergrowth) which occurs upon addition of a minimal amount of moisture to the regular carbon nanotube synthesis atmosphere. Not only does this supergrowth technique allow ultra high-efficiency synthesis of about 1,500 times in time efficiency, but it also yields SWNT of an ultra high purity of 99.98% in the unpurified state, thus achieving a major breakthrough in synthesis.

Using this supergrowth technique, we have become the first to succeed in preparation of a patterned vertical array structure of SWNTs (Photo 2). The industrial value of this technology is immeasurable. In addition, the technique has also brought about a great new leap forward in development of applications of the SWNTs in bio and electronics fields, and is thus anticipated to sustain the future industry of Japan in diverse ways.

Photo 1. A folded-paper crane made using a high quality SWNT sheet

Research Center for
Advanced Carbon Materials
Motoo Yumura

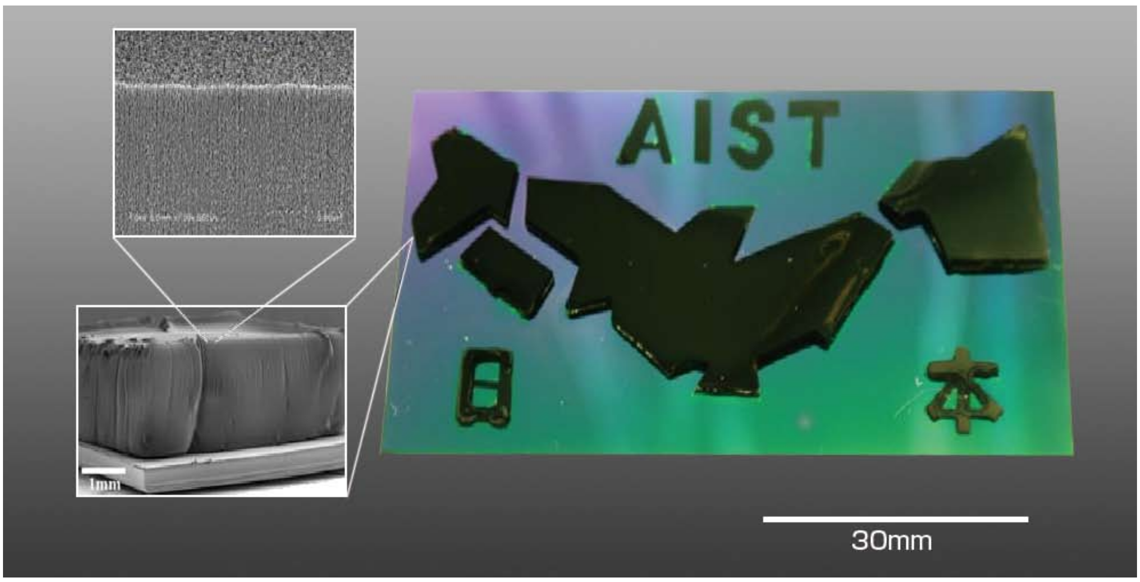


Photo 2. Carbon nanotubes which 'sustain Japan' (map of Japan made using vertically arranged SWNTs)

Structural evaluation technique for nanocarbon materials

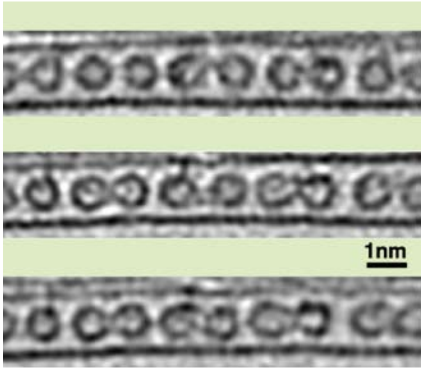


Figure 3. HRTEM image of (C_{60}-C_3NH_7) in SWNT, imaged continuously at 2-second intervals

A distinguishing feature of nanocarbon materials is their diversity of structure and physical properties. Meanwhile, without performing definite structural determination of individual nanocarbon materials at an atomic level, we are not able to predict the properties accurately. Hence, the establishment of a detailed structural analysis technique enabling quality control at an atomic level is essential to the industrialization of nanocarbon materials.

We aimed to develop an evaluation technique for exhaustively determining the structure of carbon nanotubes (CNTs) in particular.

Determination of optical isomers

The chiral index which describes the helicity of a CNT is the most important factor in determining the electrical properties of the nanotube. However, analysis of the chiral index alone is not sufficient to determine the inter-layer relationships of multilayer nanotubes. Even once the chiral index is determined, there exist optical isomers, so a double-walled carbon nanotube (DWNT) as shown in Figure 1 could potentially consist of any of four different structural isomers. Therefore, in order to completely determine the structure of the DWNT, a technique for discriminating the direction of the winding of the graphene sheet (a single layer in the graphite structure) is required, in addition to the chiral indices. We have developed a method for determining a unique structure among these four isomers, by carefully tilting the sample within an electron microscope using the measurement principle shown in Figure 2.

Direct observation of individual functional groups of fullerene derivatives (C_{60}-C_3NH_7)

The chemical modification of fullerenes is of high interest in the fields of physics and chemistry. However, direct observation of a single modified fullerene at a molecular level had not been achieved up to present. We succeeded in directly observing the C_{60}-C_3NH_7 molecule inserted in the single-walled carbon nanotube (SWNT), using high resolution electron microscopy (HRTEM) (Figure 3).

Further, as a result of the analysis of the nitrogen chemical state contained in the functional group by using electron energy loss spectroscopy (EELS), we have found that there is a strong interaction between the functional group of fullerene and SWNT.

Through development of an ultra high-sensitivity electron microscope system, we are taking on the challenge of structural analysis of new carbonaceous substances at an atomic level, which has been conventionally difficult. The atomic structure of a nanocarbon material is the most important factor to determine its physical properties, thus our achievements mentioned above which enable the precise properties prospections are expected to contribute to the expanding market of nanocarbon application in a large way.

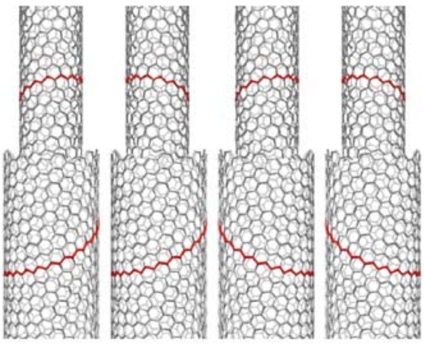


Figure 1. Optical isomers of DWNT

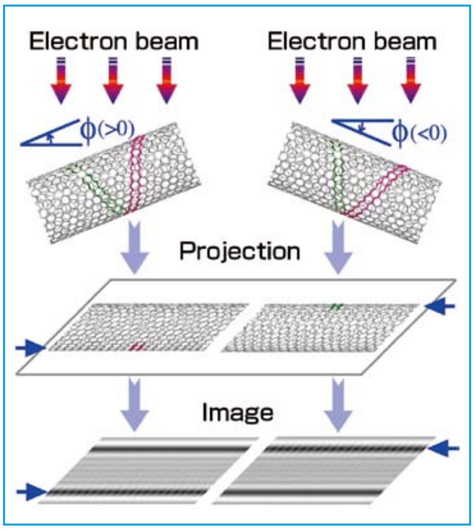


Figure 2. Discrimination of clockwise/anticlockwise winding of carbon nanotubes by sample tilting method

Research Center for Advanced Carbon Materials
Zheng Liu
Kazutomo Suenaga

Beyond silicon technology

In the spring of 2006, the news that "a notebook PC equipped with flash memory instead of a magnetic hard disk is to be released" was announced in successive press releases. As yet, we are not able to imagine that use of the magnetic hard disk as an ultra-high capacity information-recording medium for servers would ever become obsolete. At any rate, however, the role distinctions in PCs establishing that "information processing by semiconductors" and "information recording by magnetic devices" are becoming a thing of the past, owing to progress in silicon technology. Besides the above, we are recently encountering flash memories used in all sorts of personal items, such as the recording media for cell phones and digital cameras.

As you may be aware, this memory, having a high capacity and low bit cost with a recent eye on high speed as well, has been developed through leading-edge silicon technology which controls structures in the nanometer level. In this sense, we could be wondering what all the fuss is over 'nanoelectronics' now.

Meanwhile, no matter how far the performance of silicon technology is enhanced through ultra-miniaturization technologies, it will reach its limit some day. Regarding the flash memory mentioned above, if nanometer-size fabrication progresses at the current rate, concerns are arising that an inevitable operating limit will be reached around the year 2010.

At AIST, we are already advancing research and development in nanoelectronics, which goes beyond silicon technology, in an effort to avoid sudden confusion at such a time. The objects of our research and development can be roughly classified into "those that show characteristics exceeding silicon devices" and "those of a principle of operation differing from silicon devices." A representative example of the former is the development of materials and devices using silicon carbide and diamond semiconductors, which have high thermal conductivity and are superior in performance to silicon in uses requiring power. Below I would like to focus on and introduce typical examples of the latter type (the former is presented in page 11 of this pamphlet).

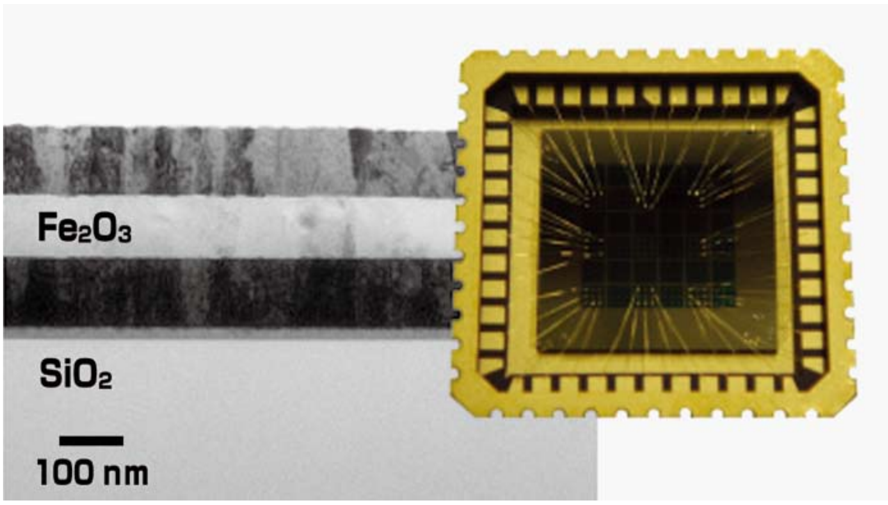


Figure 1. Cross sectional transmission electron microscope image of resistance random access memory structure consisting of iron oxide (left), and the prototype memory device of the same (right)

Nanoelectronics using functional oxides

One of the reasons that silicon technology has shown such great success can be attributed to our success in developing the technology to form silicon dioxide (SiO_2), an oxide of high insulation properties, flatly on an atomic level. However, in the realm of single digit nanometers, even this superior insulator is unable to head off the leakage of electrons. Such is the reason behind the active research into gate dielectrics using new oxides having high dielectric constants.

Meanwhile, some oxides, when applied with an electric field, for example, demonstrate significant change in electrical conductivity. At the Nanotechnology Research Institute at AIST, we are conducting research on characterization of such functional oxides also targeting application to memory, in partnership with the Correlated Electron Research Center.

Figure 1 is a photograph of a device used to demonstrate the functioning of a resistance random access memory, using iron oxides having roughly the same composition as the iron sand found at your feet. Of the future-generation candidates under research and development as nonvolatile memories that maintain data records without supply of electric power, such a resistance random access memory, in particular, is regarded as extremely promising from various perspectives including good compatibility with silicon technology and a high-intensity change of signal.

Now, the other major reason why silicon technology has been so successful is that nanofabrication technologies, or various etching technologies, in particular, were successfully developed. For example, the selective milling (or etching) of only the Si in SiO_2 can be achieved through vapor-phase etching using an appropriate reactive gas. In the following section, I would like to discuss developments in this etching process.

Nano spin-electronics

Whereas in existing electronics, devices are operated by controlling the flow and quantity of electrons, another research under way now works to develop devices based upon a new principle using spin, the other degree of freedom of electrons. Spin is sometimes likened to the rotating movement of electrons, and clockwise and anticlockwise rotations are defined as “up” and “down” spins, respectively. A familiar image is offered by the permanent magnet. Roughly stated, if the spins are aligned in one direction, magnetization occurs. New devices can be designed exploiting properties such as the magnetization being nonvolatile, or the spin inversion being of ultra-high speed.

A representative example of a familiar spin electronics device already in use around us is the data read head of hard disks. In the near future, we are likely to see practical application of a magnetic random access memory consisting of a film stack of ferromagnetic metals and insulators. If so, is a nanofabrication process such as that which led silicon technology to success being developed to allow such practical application?

The answer is No. Owing to the background that process development, while being an aggregation of technical know-how, has not been treated as a science, there are no existing systematic research and development technologies for it.

At the AIST Nanotechnology Research Institute, we are conducting development of a reactive ion etching process, in preparation for the upcoming ultra-fine fabrication of spin electronics devices. In addition, with the aid of computer simulation, we are also developing techniques for speedily advancing such research and development.

Figure 2 shows the cross section of the structure of a ferromagnetic alloy, called NiFe, etched using plasma of mixed gases consisting mainly of methane gases, observed using a scanning electron microscope. We were able to increase the selectivity against the Ti metal mask to almost infinity. The technique is anticipated for future use in nanofabrication of ferromagnetic metals.

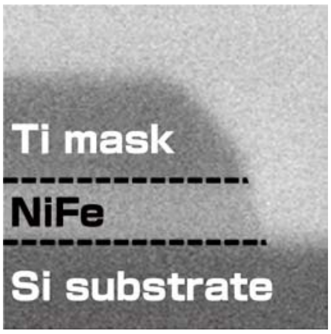


Figure 2. Cross sectional scanning electron microscope image of structure of NiFe (Permalloy) processed by reactive ion etching using Ti (titanium) masking (black dotted line has been added to show boundaries between materials)

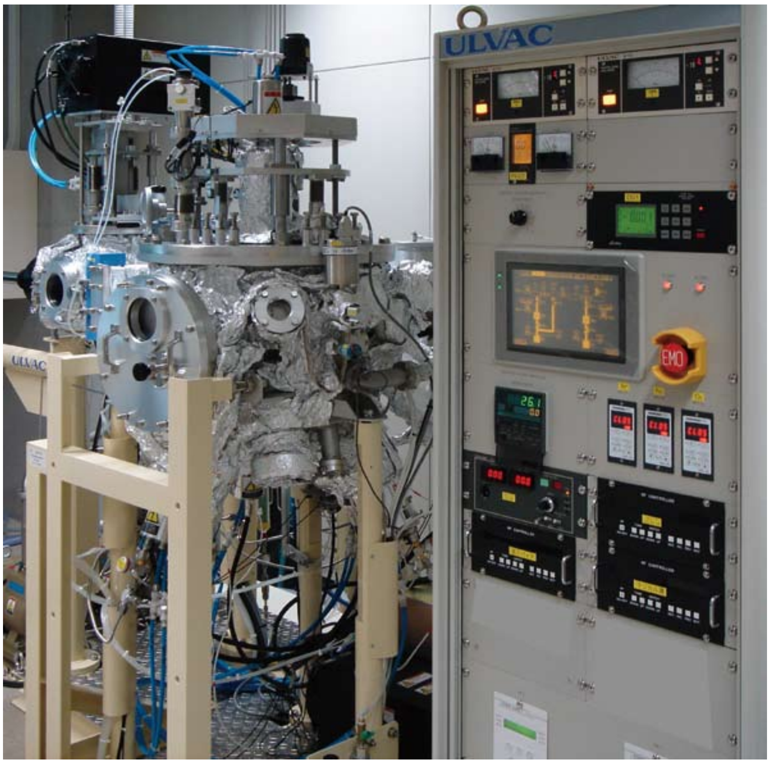


Photo. Sputtering system equipped with radical oxidation source for fabricating thin film of a transition metal oxide (the function of transition metal oxides changes largely depending upon the oxidation state, thus establishment of the thin-film deposition know-how is essential in the development of memory)

Nanotechnology Research Institute
Hiroyuki Akinaga

Advanced Device Materials

Correlated electron materials and electronics applications

What are correlated electron materials?

Semiconductor electronics centering on silicon technology can be considered the upholding force behind the household electric appliances to information and communications equipment of today. Owing to nanotechnology which miniaturizes to the level of 10 nm, semiconductors are becoming increasingly high-density and high-capacity. In such a nanometer-scale size, however, other physical phenomena may appear, leading to concerns that devices will not have conventional functionalities any more. Correlated electron materials are examples of electronic materials which have the potential of breaking through this limit.

In a simplified view, the semiconductor device may be thought to have device functionalities by controlling each individual electron among a small number of electrons (minority carriers). In correlated electron materials, on the other hand, a large number of electrons are strongly interacting with each other, forming the electronic phase.

Under certain environments, the correlated electron material behaves like an insulator with its electrons unable to move. By applying a small external stimulus, it makes a transition to a metallic phase in which its electrons move freely. This phase switching can be as fast as one picosecond or less and the gigantic phase-response of electrons can be realized. The fundamental concept of correlated electron technology is to utilize the outputs associated with changes in correlated electron phases, and to develop this phenomenon into new electronic technology.

Examples of correlated electron materials are transition metal oxides having perovskite structures, including the high-temperature superconducting copper oxides, and manganese oxides which demonstrate colossal magneto-resistance (CMR) effect. In addition, organic charge-transfer complex crystals are also correlated electron materials. Here, we would like to introduce typical examples which are expected to evolve into strongly-correlated electronics in the future.

Towards strongly-correlated electronics

A phenomenon has been discovered in which, by attaching metal electrodes to both sides of perovskite manganese oxide films and applying a pulse voltage, it switches from high resistance to low resistance at high speed. As this low-resistance state is stored until the following reverse bias voltage pulse is applied, it is expected for future application to large-scale high-speed nonvolatile memory (Figure 1).

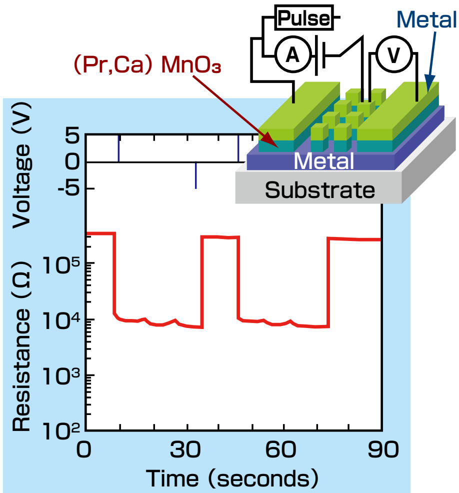


Figure 1. Colossal electro-resistance (CER) memory effect of perovskite manganese oxide

Ferroelectrics are important device materials which are widely used for electronic applications such as nonvolatile memories and piezoelectric elements with polar inversion. Recently, we have succeeded in development of new organic ferroelectrics having a huge dielectric constant even at room temperature (Figure 2). These organic ferroelectrics have been desired for the future organic electronics which can realize the excellent functions flexibly in lightweight materials.

In addition, we have discovered that irradiating laser light on perovskite cobalt oxides and manganese oxides causes them to make an extremely high-speed (sub-picosecond) transition from the insulator to metallic phases. They are thus expected for use in devices of ultrafast optical switching or magnetic switching by light irradiation.

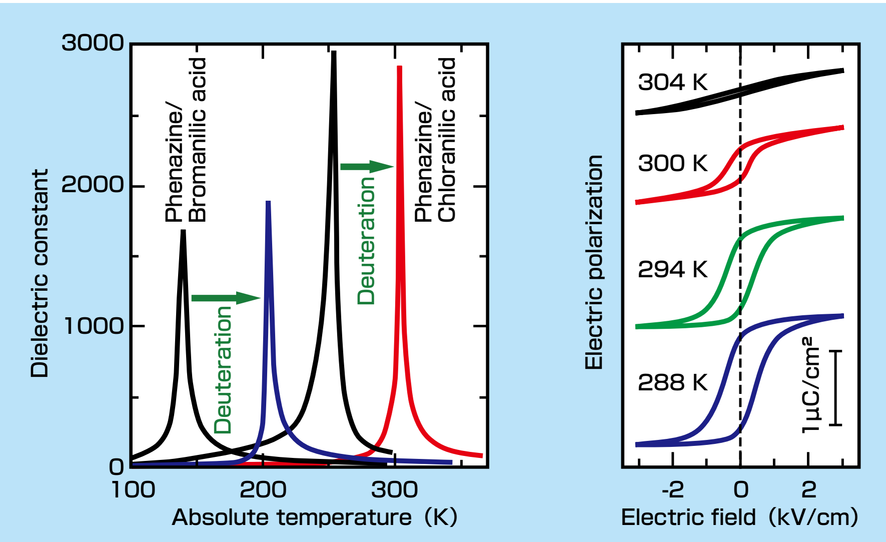


Figure 2. Dielectric property of a new organic ferroelectric material in which 2 species of π-electron molecules are bounded by strong hydrogen bonding

Correlated Electron Research Center
Hiroshi Akoh

Toward electronic application of diamond

Although diamond is popular to us as a jewel, it is a quite unique material with many excellent characteristics. Owing to progress in the synthetic methods of vapor-phase deposition, diamonds are now available not only in particle, but also in sheets and thin films, thus their application may be expected so widely. Current status of research and development to use diamond as an electronics material for devices is active to contribute in environment, bio technology, measurement technology, etc.

Diamond devices?

The advantage of diamond may be recognized as to have the prime characteristics such as the highest hardness, the highest thermal conductivity, optical transmittance, excellent semiconducting characteristics, etc. Thus, it is anticipated to be developed for wide-range applications. Recent progress of the technology to process diamond in nm scale has expanded the range of devices fabrication. In addition, it has also been revealed that atomic level control of the surface significantly affects on the surface properties, making diamond applicable to uses such as sensors. Followings are the introduction of the devices which are under development in Diamond Research Center (DRC).

Semiconductor devices: Some physical properties of diamond are regarded as the ultimate among semiconductor materials, and diamond is a candidate as the post-silicon material. Owing to its expected device characteristics of high-temperature operation and high breakdown voltage, it is regarded as the material best suited for high power applications. However, there still remain many basic issues to be developed, such as high-quality epitaxial layer, doping, and control of interface, in order for it to prevail in the competition with materials preceding it such as silicon carbide (SiC) and gallium nitride (GaN).

Electron emitting device: Diamond has negative electron affinity under certain surface states and is a material which can emit electrons easily. Many attempts were carried out to show the potential of as an electron source with low turn-on voltage, high-current and low-temperature operations. Also, diamond is considered to be good material as secondary electron emitting.

Biosensor: Diamond can immobilize biological materials, such as DNA, protein, etc. on the surface, which may be modified into various characteristics. Diamond has a wide electrochemical potential window and biocompatibility. It is anticipated for use in various biosensors using these characteristics, and further, use within the body is not a dream thanks to its biocompatibility.

Development of research at AIST

DRC is researching toward the applications mentioned above. For example, we are working on improvement of breakdown voltage of Schottky junctions, on the surface structures that allow low-voltage electron emission and on the sensor detecting bio materials. In particular, an ion sensitive field effect transistor (ISFET) type pH sensor (Figure 1) using single crystal diamond was developed, and has succeeded in achieving high sensitivity (Figure 2). In addition to developing the device itself, we are doing some basic studies on the characterization and the surface modification of diamond, including immobilization of DNA. Further, we are working as well on manufacturing technologies for large single crystals wafer which looks very important material in electric application. Already, we have succeeded in growing a single crystal up to 10 mm in thickness using a chemical vapor deposition, and hope to make progress to single crystals in the inch size in the future.

As described above, we will develop realistic devices and transfer our research results in industry and promoting the wide use of diamond devices in various application fields.

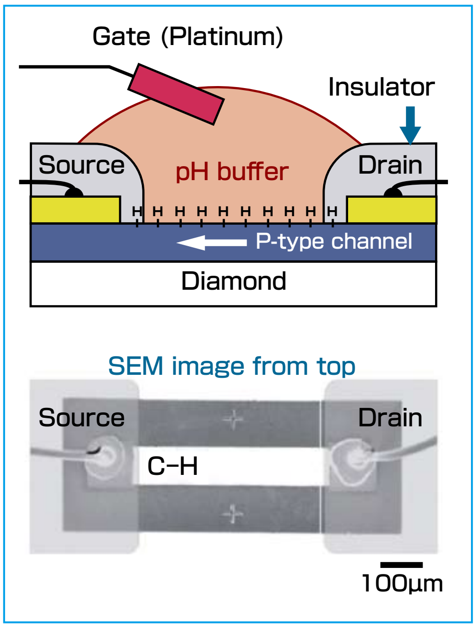


Figure 1. Schematic diagram of diamond pH sensor and SEM image

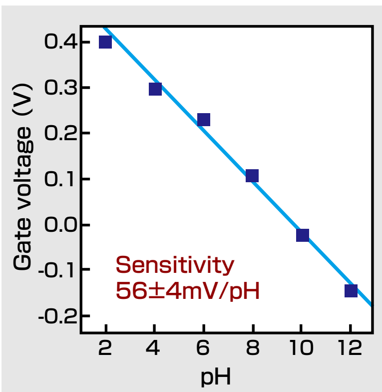
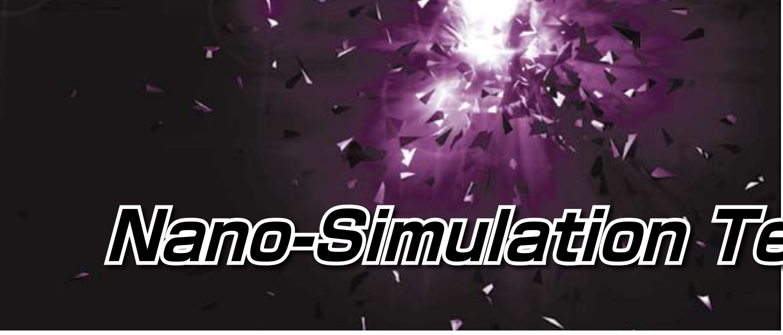


Figure 2. Sensitivity characteristics of diamond pH sensor

Diamond Research Center
Naoji Fujimori



Nano-Simulation Technology

Simulation leading the way in nanotechnology

The nano world

A characteristic of nanotechnology is that, unlike when viewing materials and devices in the macro, the atoms, molecules and electrons become exposed explicitly in their properties. Therefore, phenomena which are unpredictable by any ordinary sense can occur, such as the quantum effect and various other effects arising from the nano size.

As such phenomena cannot be readily or fully understood through experiments, simulation becomes an important aspect. Furthermore, new nano-phenomena can even be predicted through simulations, which could potentially lead to the creation of new technology and new industries.

Nano-simulation

The nano-simulation targets such nano-scale phenomena. The nano-simulation technology is the collection of various simulation techniques, and at the same time constitutes the function linking them. The main tools used are electronic state calculations to see the quantum effect generated by electrons, and molecular dynamics calculations to see dynamics of atoms and molecules based upon the interactions between them.

Although these nano-simulation techniques already have long histories of development, their platforms as industrial technologies are weak compared to what we may call the macro calculations such for structural mechanics and fluid dynamics, thus they need to be developed intensely. To this end, we are advancing method development and simulation work in parallel, some examples of which I would like to introduce below.

Electron transport in the nano-scale system, and its application

Devices using single-molecule and carbon nanotubes are currently proposed for the purpose of overcoming the size limit of present silicon devices, and their operation has been confirmed experimentally. Simulation is utilized to gain a true understanding of these systems and to predict their functioning. Inelastic scattering of conduction electrons by intramolecular vibration is an example of the functions. We lead the world in constructing this electron state theory, so that these studies on real molecule/electrode systems are enabled.

In addition, after the theoretical work on the carbon nanotube, we have proposed an idea that the tensile force and hydrostatic pressure on it can be determined from electrical conductivity measurement. For this, a magnetic field is applied in parallel to the axis, as shown in Figure 1, and the electrical conductivity is measured. The curvature effect of the nanotube as well as the mechanism of the electron scattering effect can be determined. We hope that the experiments we proposed will be done and quantum effect devices using these materials will be realized.

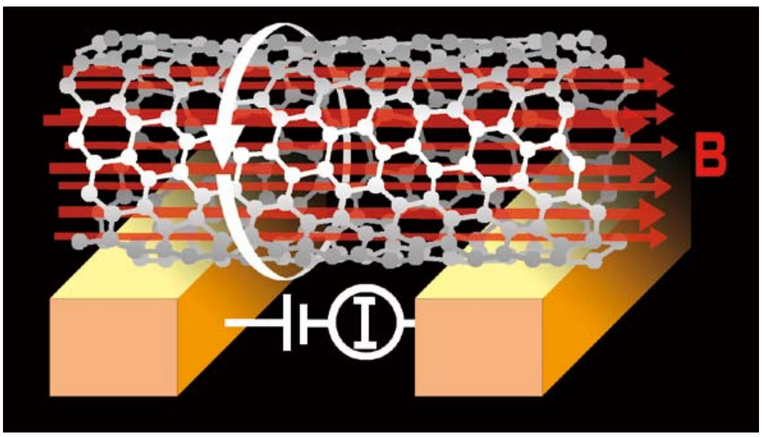


Figure 1. Correlation between electrical conductivity and environment of the carbon nanotube

The nano-size cluster

Most of materials familiar to us, when viewed microscopically, are made from crystal such as closed packed or diamond structures. However, further in the nano size, structures which are geometrically impossible in bulk become possible, making way for new potential functions. Regarding such new materials, we are required not to simply indicate their structures, but also indicate a possible way for their synthesis. Below, I introduce the nanocluster and nanowire of silicon possessing a 5-fold axis of symmetry as an example.

If we create a silicon droplet by molecular dynamics simulation and maintain it at a temperature slightly below its melting point, it forms a silicon cluster having a regular icosahedral structure, which cannot possibly exist in bulk (Figure 2). It is believed to take on the structure having the lowest surface area so as to decrease the number of dangling bonds in the system overall. Further, by similar moleulcar dynamics simulation of Si in a certain confined space, we find that a nanowire having 5-fold symmetry in the axis direction is formed. Presently, we are in determining the electronic states of these substances to see the electrical properties.

Elucidating nanodoping of diamond

Due to the fact that diamond is a wide band gap semiconductor having an energy gap of about 5 eV, diamond should possess electrical properties overwhelmingly superior to silicon. In reality, however, its doping efficiency is too low to create sufficient numbers of electrons or electron holes at room temperature because of deep energy levels of the dopant impurity atoms.

In order to resolve this problem, the Research Institute for Computational Sciences, in cooperation with the Diamond Research Center, has performed first-principles calculations to elucidate the nanodoping mechanism of diamond. For example, as in Figure 3, when a phosphorous atom (a donor impurity) is doped in near-surface regions of diamond where the surface is hydrogenated, we are able to know what kind of stable structure occurs.

We expect that these computations may serve as the first step in our atomic scale understanding of the recent experiment in which the doping efficiency of phosphorous atoms is largely dependent upon surface orientation. We have also performed thermodynamic analysis of the doping efficiency, in order to contribute to resolving the practical issues of diamond doping.

Development of the software for nano-simulation

In simulations such as described above, most often we are not able to simply buy the software and then commence with simulations, but instead start with the work of making the computation program itself. We are investing large efforts into development and release of such programs aiming for large scale, high speed, high precision, and high performance in simulations.

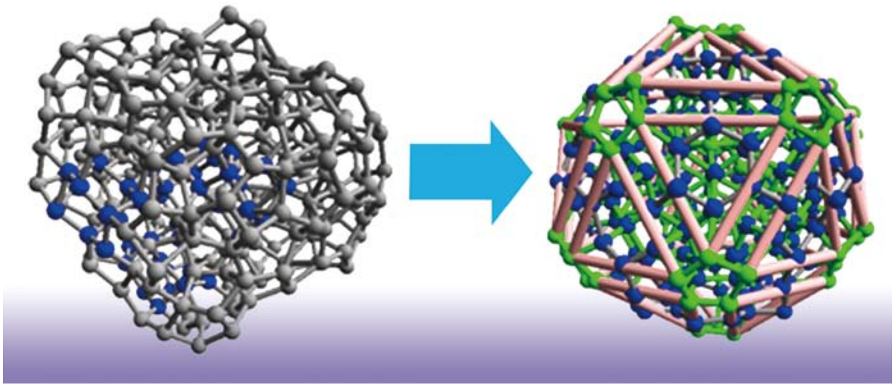


Figure 2. Simulation results of formation of a silicon regular icosahedral cluster

OpenMX (numerical and local basis density functional theory code): A program suitable for electronic state calculations of large-sized clusters and such. In cooperation with researchers worldwide, we are currently in enhancing its functions to make it capable of calculating various properties. In particular, it caters to targets that were not readily calculated by conventional software, such as non-collinear magnetization and electron transport. Moreover, while the computation time for electronic state calculation generally increases proportionally to the third or fourth power of size, we have developed and incorporated several techniques to make it linear, to accommodate large-scale systems.

MPDyn (classical molecular dynamics code): Mainly targets molecular assemblies, but is also applicable to metals and inorganic materials. It is utilized, for example, in high-precision calculations of free energy in molecular membranes, and calculations of polymer electrolyte membranes used in fuel cells.

FMO (fragment molecular orbital method): Divides large molecules such as proteins into small units, realizing high speed and high precision by calculating each unit with its pair. It is opened incorporated into the international free software GAMESS. It has a record of completing electronic state calculations of a protein of 20 thousand atoms in three days (600 cpu used).

In addition to the above, we are also developing QMAS based on PAW method, FEMTECK using finite element basis, and PEACH which can use forces from FMO for molecular dynamics calculations.

Research Institute for Computational Sciences
Tamio Ikeshoji

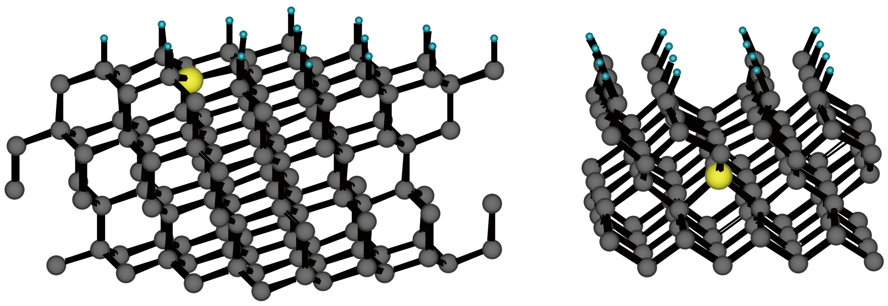


Figure 3. Optimized structure of phosphorous impurity atom (yellow) in surface region of hydrogenated diamond, Left: (111) surface, Right: (001) surface

Nano-Characterization Technology

International standardization in nano-characterization technology

Need for standardization in nano-characterization technology

Recently, the need for industrial standardization in nanotechnology is being recognized from two perspectives.

The first perspective originates from the growth process where nanotechnology evolved from the laboratory to the market. It is what is known in industrial design theory as the “modular” form, and is an inevitable request in the progress of the nanotechnology industry. The underlying reason may be that, even if nanotechnology were assumed to progress in the “integral” form, a qualitative changeover will be required in the nano world, from the conventional “experiential alignment” to “scientific alignment.”

The other is awareness arising from an aspect regarding the social acceptability of nanotechnology. Currently, we are beginning to hear alarms raised regarding acceptance of “nanotech” technologies and their related products, based on observation reports regarding the biological impacts accompanying nanoparticle administration. When asked, “Were the observed cases of biological impacts truly attributable to the effect of ‘size,’ or were there not other fundamental factors involved?”, however, nobody is able to offer any clear guidelines. For this reason, there is need to establish the techniques for measuring and evaluating the size and shape of nanosubstances or the types and quantities of impurities they contain, as well as to standardize the testing and evaluation methods based upon these techniques.

Movements toward international standardization

Standardization movements in nanotechnology have rapidly intensified since 2005. First, the new Technical Committee on Nanotechnologies (TC229) was established within the International Organization for Standardization (ISO) upon active participation by many leading countries (30 participating member countries, of which 7 are observer members), and its first meeting was held in November 2005. The second meeting was held in Tokyo, in June 2006, and we are steadily gaining a view of the standardization promotion strategies of each country. The international promotion scheme established as of present is as shown in the Table.

Japan (as well as USA) is advancing activities based upon the policy of making active international contribution through the standardization of measurement and evaluation techniques for what are called the artificial nanomaterials such as carbon nanotubes and fullerene.

Initiatives by AIST

In addition to playing a central role in administering the main domestic deliberations organization for ISO/TC229 action, AIST is reviewing the draft of items for international standardization based upon various needs, as well as advancing development of the measurement and evaluation technologies thereof. For example, results of a questionnaire survey conducted in February 2005 revealed that demands regarding evaluation for the form (shape) of nanostructures of level 1-50 nm were highest. For this target size and purpose of measurement, utilization of the atomic force microscope (AFM) is essential. However, in morphological observation of nanosubstances and nanostructures by AFM, a problem as indicated in the Figure has been identified. In order to overcome this problem, establishment of the technique and procedures for on-the-spot evaluation of the shape of the apex of the AFM tip actually used for measurement is essential. In light of this situation, we are working on the preparation and development of a new tip characterizer, as well as research and development aimed at achieving international standardization of precise morphology measurement of nanosubstances and nanostructures utilizing this tip characterizer.

Research Institute of
Instrumentation Frontier
Shingo Ichimura

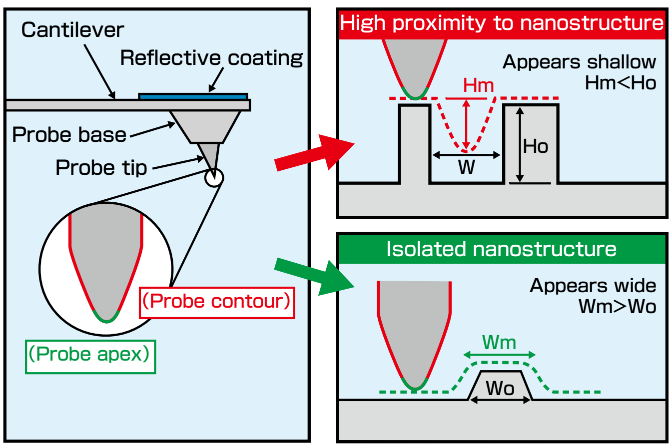


Figure. Schematic diagram indicating the problem in morphology measurement of nanosubstances (structures) using AFM
The development and supply of a tip characterizer which is capable of on-the-spot determination of the tip shape of the AFM probe used (probe characteristic function indicating the degree of minuteness of structure observable using that probe) holds the key to international standardization of precise morphology measurement

Table. International ISO/TC229 scheme

Working group	Convener
1. “Terminology and Nomenclature”	C. Willis (Canada)
2. “Measurement and Characterization”	Shingo Ichimura (Japan)
3. “Health, Safety and Environment”	S. Brown (USA)

International Chairman: P. Hatto (UK)　Secretary: J. Alcota (UK)

A new molecular sensor utilizing organic molecules

Today, people become more conscious of environment and safety/security issues. Detecting trace amounts of toxic substances and preventing health hazards caused by them are of high interest. In addition, with the coming of the aging society, there are demands for early discovery and care for diseases through simple home health checks. To meet these social requirements, novel measurement technologies that lead to a new paradigm need to be constructed based on the nanotechnology. As a typical example, we are developing new highly-selective and highly-sensitive molecular sensors which take advantage of the characteristics of organic molecules.

Nanotechnology utilizing organic molecules

Organic molecules possess many characteristics which are not found in other materials, one of which is "smallness." Generally, the molecules are of a size in the nanometer level, and they can be further imparted with functions to identify specific chemical substances and selectively react with them. Meanwhile, developments are in progress in diverse fields for instruments that may contribute to human society. In these instruments, the parts used are made "smaller" to further heighten integration and performance. If we could use organic molecules as nanoscale parts, such possibilities would be extended.

We have developed a simple technique for making electrodes (Figure 1) possessing gaps with the size of organic molecules (nanogaps), to enable organic molecules to be used as parts. Upon setting the molecules into the gaps of the electrode, we are conducting evaluation on the changes in conductivity under various conditions. Organic molecules are inherently suited to serve as nanoscale constituent elements in minute systems.

Towards development of a new chemical sensors

We are developing "molecular sensors" for detecting specific substances in the world around and inside us. Utilizing the characteristics unique to organic molecules, we are trying to develop various sensors that are distinctly different from inorganic types (silicon devices in particular). Following is an overview of our research on an electric potential measurement type sensor using a molecular ultrathin films.

Sensors detecting potential change as the signal have the advantages of having a simple device structure and allowing miniaturization of electrodes, since the potential change takes place at any size of the surface area in principle. We synthesized various organic molecules, which were then adsorbed on the nanoelectrode surface to achieve selective molecular detection (Figure 2). We achieved a high sensitivity of top level worldwide, as the electrodes are nanoelectrodes and require only a minute amount of substance to be captured. The newly synthesized organic molecule automatically adsorbs and modifies the minute electrode, and it captures the approaching specific molecule targeted for detection, which causes a change in the electric polarization. This change in surface state is detected as the signal.

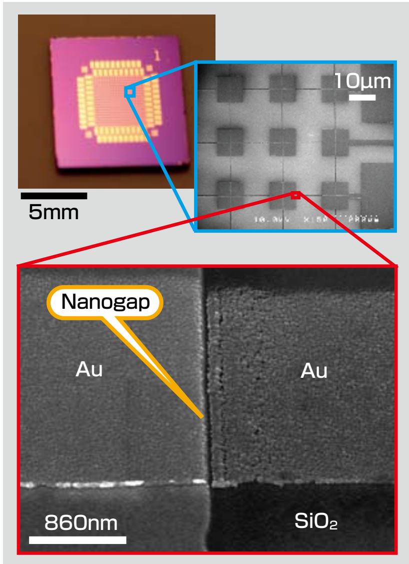


Figure 1. A chip integrated with 800 nanogap electrodes and its SEM photograph magnifying a nanogap part (molecule-sized gaps are constructed)

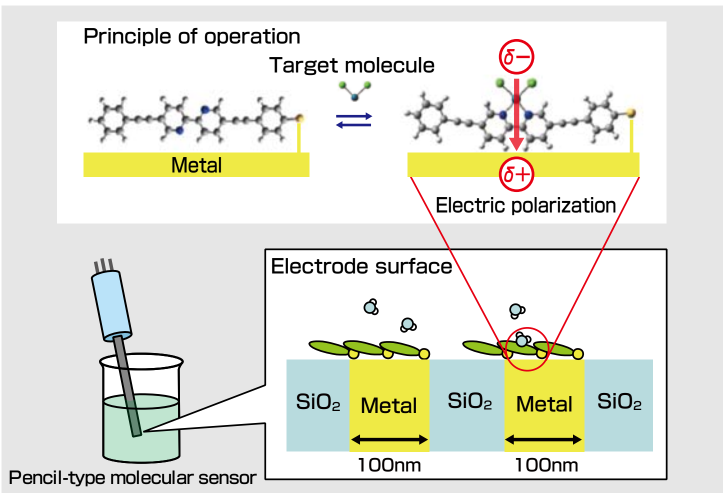


Figure 2. Electrode modification and principle of operation of pencil-type molecular sensor used in solution (when the target molecule was captured by the organic molecule adsorbed on the nanoelectrode surface, electric polarization is induced on the surface, and this change is detected)

This research was conducted as a NEDO-sponsored research, jointly by the Nanotechnology Research Institute and the Nanoarchitectonics Research Center, utilizing AIST-NPF.

Nanotechnology Research Institute
Tohru Nakamura
Yasuhisa Naitoh
Wataru Mizutani

From nanobiotechnology to medical application

Nanobiotechnology, an area of fusion between biology and nanotechnology, has recently been attracting attention and making rapid progress.

AIST, led by its Nanotechnology Research Institute, is actively advancing research on applications to medicine utilizing such technology. Below, I would like to introduce some representative examples.

Target-oriented drug delivery system

Winning the battle against cancer is one of the greatest issues of 21st century medicine. Drug delivery systems (DDS) which are capable of delivering anticancer drugs selectively and intensively to the affected area are commanding high interest as the trump card in this battle.

We have focused our attention on the cell-recognition function of sugar chains to advance development of a DDS that will launch a missile attack against cancer cells.

DDSs known up to now relied solely on the sustained release of drugs captured within the vesicles. They were passive, showing little or no recognition action for the affected area, whereas AIST's sugar chain type drug delivery system has demonstrated high selectivity for the affected area in the results of recent animal experiments.

Development of a cell culture dish using the nanopillar sheet

It is possible to make fine structures in the nanoscale on the resin on a substrate using nanoimprinting technology. The result is called a nanopillar sheet. The Nanotechnology Research Institute, in a corporate joint research effort, has discovered that the nanopillar sheet can be used as a novel type cell culture dish.

The nanopillar sheet, as shown in Figure 1, consists of column-shaped nanopillars arranged at equal spacing, upon which living cells can be cultured. The cells contact the heads of the nanopillars and multiply by division supported on top of the nanopillars.

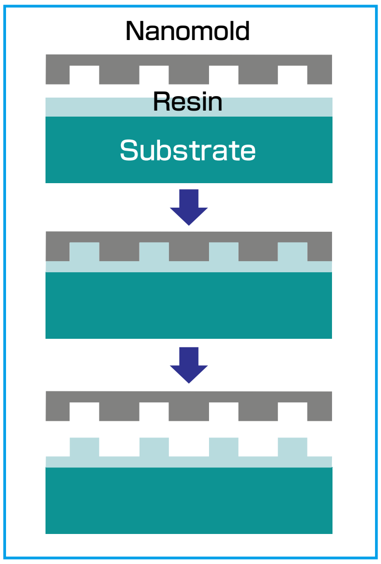
In regular cell culture dishes, passage (subculture) of the cultured cells is performed by stripping the cells by means such as enzyme treatment, as the cells are strongly adhered to the dish. The nanopillar sheet, however, has the features of allowing cells to be collected simply by pipetting, and of readily allowing the formation of spheroids. Therefore, it is attracting attention as a novel cell culture dish with characteristics which makes it applicable to fields such as regenerative medicine.

Development of technologies for restructuring living tissue

Techniques available for restructuring lost tissue include transplanting biomedical tissue to the affected area or culturing the materials and stem cells (cells which constitute the seeds of all cells) in vitro and then transplanting them to the diseased area for regeneration (regenerative medicine: tissue engineering). A method is also available in which growth factors are adsorbed onto a material to induce cell regeneration through sustained release within the living body.

Based upon such techniques, we are undertaking research aimed mainly at regeneration of hard tissue (bones and cartilage, as well as teeth).

Let us start from the tip of the head. Complete regeneration of the cranial bone is not possible using the medical material apatite which is used in cranial bone formation in cranial nerve surgery. In an effort to remedy this situation, we are advancing research aiming at complete regeneration of the cranial bone. We adsorbed FGF, a growth factor having a bone formation stimulatory effect, onto the medical material and transplanted it to the affected area to activate the surrounding



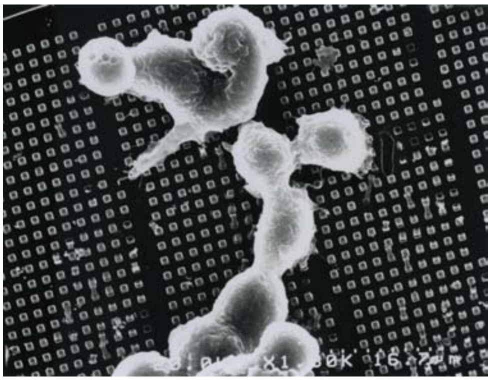


Figure 1. Method for preparation of nanopillar sheet using nanoimprinting technology (left) and electron microscope photograph of HeLa cells cultured upon nanopillars (diameter 0.5 µm) (right)

cells by sustained release of FGF, thereby promoting bone formation.

Next, periodontal disease, which affects anybody with increasing age, is a disease in which the alveolar bone supporting the teeth is dissolved and the teeth become increasingly unstable. Through joint research with a university, we have discovered that a protein found in the teeth called a phosphophoryn bonds with collagen to form nanoapatite, thereby becoming capable of bone regeneration (Photo). Currently, we are advancing development of the materials to be used in treatment of diseases such as periodontal disease using this material.

Osteoarthritis which is a chondropathy of the knee and hip joint is a serious issue of the aging society, affecting large numbers of patients. Cartilage is not readily substituted by biomaterials, thus requires regenerative treatment using autologous cells. However, cell culture of cartilage is difficult. We have already succeeded in constructing transplantable large-scale cartilage tissue from bone marrow cells, which have a large content of stem cells, using a RWV bioreactor. This bioreactor enables culturing in a state where the tissue is floating as if in a microgravity environment (space environment), using rotation of a cylindrical vessel. We are thus advancing research aiming for clinical application.

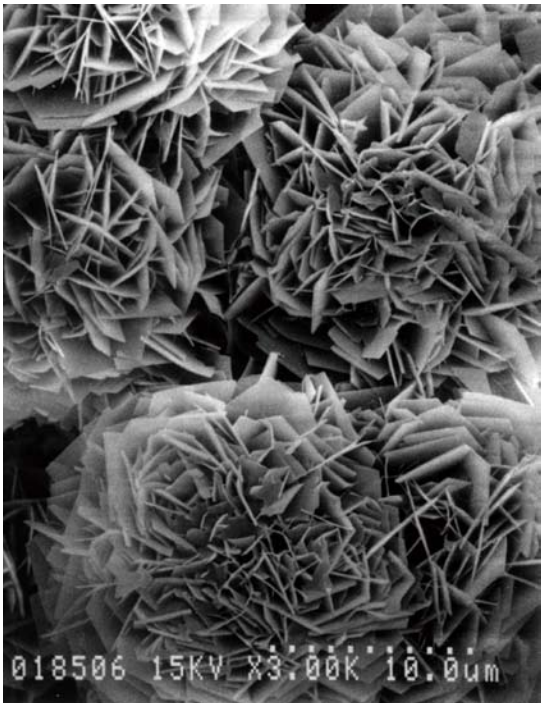


Photo. Electron microscope image of calcification by a phosphophoryn applied on agarose beads (Robust growth of apatite crystal was observed)

As hydroxyapatite, the principle component of bone, has the properties of bonding with bone and adsorbing many biomolecules in the body, it is considered for use not only as a material for artificial bone, but in wide-ranging applications. We are working on developing scaffolds for artificial bone and tissue regeneration as well as biomaterials for percutaneous devices and such, by forming apatite layers, having various compositions and structures, on the surface of polymeric materials. Conventional percutaneous devices were troubled by a high incidence of bacterial infection due to insufficient adhesion of the device to the epithelium at the contact surface, which allowed bacterial penetration. We are therefore working to develop an anti-infective percutaneous device by combining signal molecules, such as cell-adhesion agents to enhance attachment to the epithelium and antibacterial agents to kill bacteria, with apatite and polymeric materials (Figure 2).

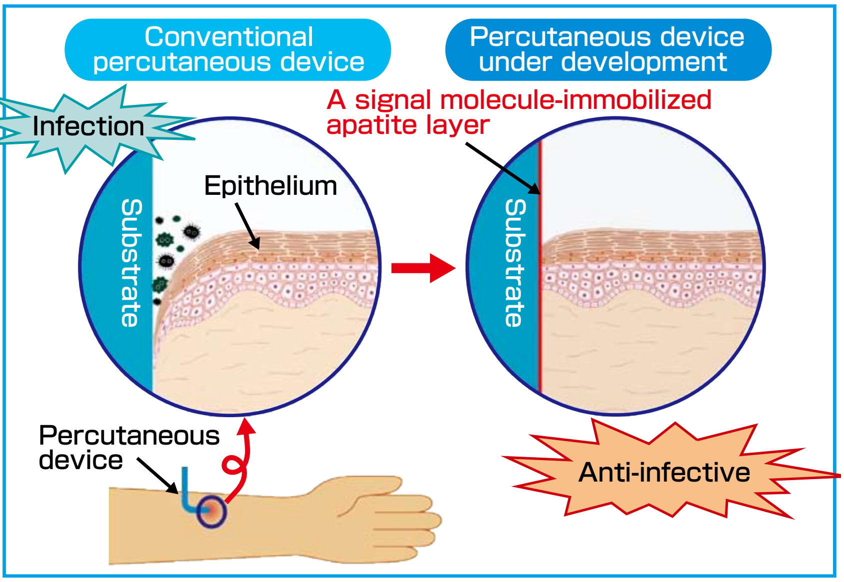


Figure 2. Development of anti-infective percutaneous device using a signal molecule-immobilized apatite layer

Nanotechnology Research Institute
Toshimasa Uemura

Nanoenvironment technology

VOC sensors using organic-inorganic nanohybrids

A new concept

Volatile organic compounds (VOC) are the substances responsible for sick house syndrome. A compact sensor capable of on-the-spot measurement of the type and concentration of VOC in the atmosphere is in demand as a means to adequately control these chemical substances. We are tackling this issue through the approach of organic-inorganic nanohybridization.

Materials consisting of a hybridization of organic and inorganic component on a nano level can be anticipated to demonstrate completely new properties, instead of just a combination of the properties of both. We have proposed a new concept for applying organic-inorganic nanohybrids to VOC sensors (Figure, left).

The concept aims to enhance the potential of the material itself by allocating the functions required in a gas sensor material, of molecular recognition and signal conversion, separately to the organic compound and the inorganic compound. A higher selectivity towards VOC could be expected compared to semiconductors using the typical conventional material of a metal oxide.

VOC gas selectivity

In order to actualize the concept mentioned above, we focused attention on intercalation type nanohybrids, consisting of layer structured molybdenum oxide (MoO_3) with organic component inserted between the layers. In the material, alternating inorganic and organic layers are stacked at crystal lattice level, each playing a distinct role. It has been revealed that the $(PANI)_xMoO_3$ thin film element – consisting of polyaniline (PANI) inserted between the layers of molybdenum oxide – demonstrates excellent selectivity, responding to formaldehyde and acetaldehyde by a reversible change in resistance, but not to toluene or xylene, etc.

A further interesting point is the diversity of possible combinations of organic component with molybdenum oxide. By changing the combination, gas selectivity may potentially be controlled. Thus, we prepared a $(PoANIS)_xMoO_3$ thin film element by inserting polyorthoanisidine (PoANIS), a polyaniline derivative, and compared the sensor characteristics to the $(PANI)_xMoO_3$ (Figure, right). While the $(PANI)_xMoO_3$ showed a higher response sensitivity (rate of resistance change) to formaldehyde than to acetaldehyde, $(PoANIS)_xMoO_3$ inversely showed a higher sensitivity to acetaldehyde. PoANIS shows a higher solubility in acetaldehyde compared to PANI, which is believed to be the reason for the high sensitivity of $(PoANIS)_xMoO_3$ to acetaldehyde. Unquestionably, the organic component is fulfilling its role of molecular recognition. This result is important from a practical standpoint as well. It signifies that, by arithmetic processing of the two different signals from the device, independent measurement of formaldehyde and acetaldehyde is possible. We are currently working on applying these results to devices.

Advanced Manufacturing Research Institute
Ichiro Matsubara

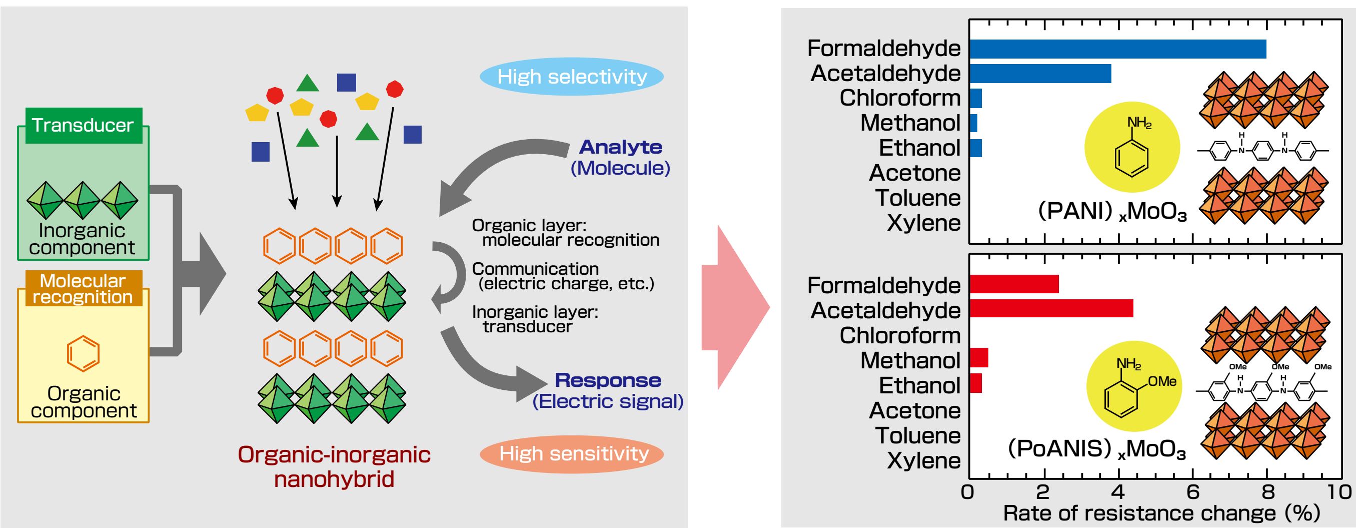


Figure. The concept of the organic-inorganic nanohybrid sensor, and response sensitivity to VOC of the organic/molybdenum oxide thin film element prepared

Development of a photocatalyst utilizing nanotechnology

Unconscious nanotechnology

Titanium oxide (TiO_2), which possesses photocatalytic functions, such as purification of air and water, antifouling (self-cleaning), and antibacterial properties, has been used since long ago as a pigment in all things white. Having a high absorbency of UV light, titanium oxide is also used in cosmetic products.

Practical application of titanium oxide as a photocatalyst began in the 1990s. It was found that titanium oxide particles of 20 nm diameter or smaller are highly active. The reasons are believed to be an expansion of surface area due to fine-graining, and shortening of the travel distance to the surface, of electrons and positive holes generated by light absorption. Photocatalysts may be the first nanoparticles to be used in our familiar surroundings.

Enhancement of performance utilizing nanotechnology

Enhanced adsorption: The effect of photocatalysts is believed attributable to the action of active oxygen species such as OH radicals which are generated on the surface upon light irradiation. In order to remove environmental pollutants, first of all, the substances must come into contact with the photocatalyst surface, which is where adsorption ability becomes a factor. At night, without light, the photocatalyst is not functioning, but if it can hold on to the contaminants using adsorption, it will be able to dispose of them at dawn.

Micro-mesopore silica material which is cast using polymers adsorbs volatile organic compounds (VOCs) in large amounts. As it also shows fast adsorption-desorption cycle, we are now studying to support photocatalysts on it (Figure A).

Enhanced selectivity: As OH radicals have a high oxidative ability, they indiscriminatingly attack nearby organic matter. If they were to destroy only the desired targets, treatment efficiency would be improved. Therefore, we are trying to achieve selectivity for specific substances by controlling factors such as surface fine structure, acidity, and hydrophilicity. We have confirmed that the surface made hydrophobic by addition of a carbon layer or modification by alkylsilane (Figure B) successfully enhances VOC degradation efficiency. In addition, we are investigating preparation of a specific structure called a nanopod (Figure C).

By using photodeposition exploiting the fact that it is a photocatalyst, it is capable of supporting highly dispersed nanosized metal particles. Using palladium-supporting titanium oxide (Photo), complete oxidation of vinyl chloride becomes possible, and with the silver (Ag)-supporting titanium oxide, stable nitrous oxide can be successfully decomposed. By inverting this configuration, new functions may also be anticipated (Figure D).

Enhanced photonic efficiency: Electron-positive hole charge separation is improved with support of metals, as is light use efficiency. However, in order to achieve efficient functioning of titanium oxide indoors as well, response to visible light is essential. The most effective doping at present has been achieved through treatment of titanium oxide under an ammonia atmosphere. By calcinating a titanium complex containing nitrogen, AIST has succeeded in increasing the uniform nitrogen concentration within the photocatalyst to enhance activity.

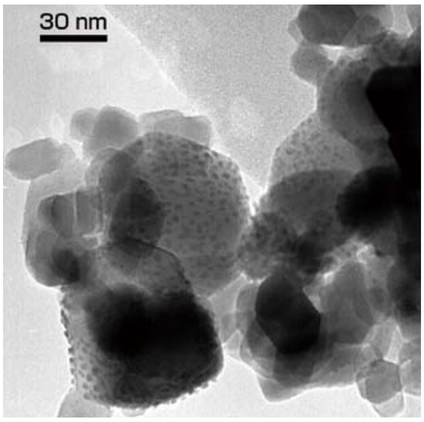


Photo. Palladium-supporting titanium oxide prepared by photodeposition

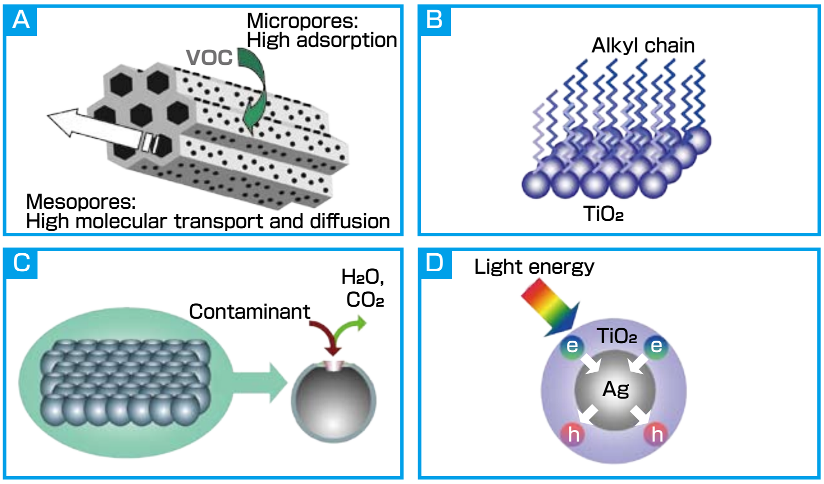


Figure. Enhancing photocatalyst performance through three-dimensional structure control
A: Utilization of micro-mesopore silica adsorbent
B: Enhancement of selectivity through surface modification (this example: improvement of VOC degradation activity by hydrophobization)
C: Nanopod possessing molecular recognition function (aggregation of TiO_2 hollow particles)
D: Photocatalyst of core-shell structure (the inverse of metal-support; aims to enhance efficiency of active oxygen generation and electron storage)

Research Institute for
Environmental Management Technology
Koji Takeuchi

A high-performance capacitor using singled-walled carbon nanotubes

Electric double layer capacitor

The electric double layer capacitor has high power (high output), is maintenance-free (high cycle life) and is highly safe. A new market is presently developing for its use as a power source in rapid preheating, as its capability of rapid discharge eliminates the necessity for standby power, thereby making energy saving possible in various equipments.

The capacitor is capable of rapid charge and discharge compared to the lithium ion secondary battery but also has the disadvantage of a small capacity of stored energy. The greatest challenge in capacitor development is to increase the stored energy, or in other words, realize a high energy density, but we have already reached the limit using the current activated carbon electrodes. Consequently, the development of capacitors using carbon nanotubes (CNTs) as electrodes is anticipated.

The potential of CNT electrodes

In order to achieve high energy density, it is essential that the electrode surface area be large. Using “supergrowth technology,” an innovative CNT growth technique (details are introduced in page 6 of this pamphlet), it is possible to prepare long single-walled nanotubes in a high-density vertical array (Figure 1), which we have named the “CNT forest.” The CNT forest possesses a large surface area unparalleled by any of the existing CNTs. Breakthrough improvements in energy density can be achieved by using it as a capacitor electrode. Further, as it does not have the contact resistance seen in activated carbon electrodes prepared by powder molding, the internal resistance of the cell ascribable to electrode material is minimized (Figure 2). This indicates that it has excellent charge/discharge characteristics as a charge storage device and is thus capable of achieving a high power density.

The project and its anticipated economic ripple effects

The “Carbon Nanotube Capacitor Development Project” was launched in FY2006, led by AIST. Although there are high hopes for CNT capacitors as they show high performance, their manufacturing cost must be drastically reduced in order to allow practical application. Development of a mass synthesis technology for CNT is indispensable to that end. This project works to develop a mass synthesis technology for CNT forests, as well as to develop a high energy density capacitor using the CNT forest.

Electric double layer capacitors of high energy density are anticipated for energy-saving uses in diverse fields, from the compact types in portable devices, to the medium-sized types in power supplies for preheating copy machines and printers. In addition, there is an extremely large market potential for large-scale types, as regenerative power sources in automobiles and railways, as well as power sources in hybrid vehicles which require high-power charge storage devices. They are thus anticipated to contribute to energy conservation in a large way.

Research Center for
Advanced Carbon Materials
Motoo Yumura

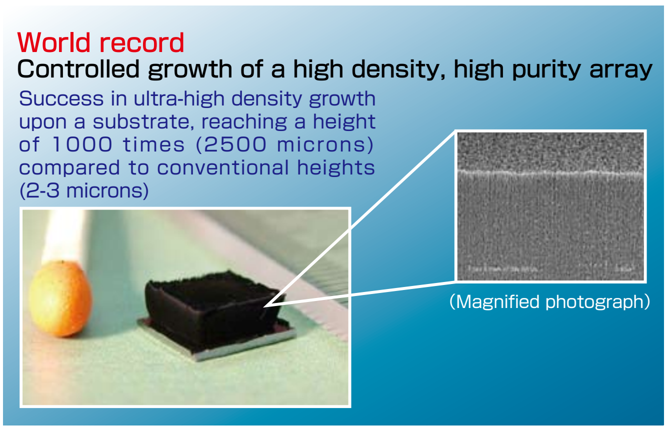


Figure 1. CNT forest (Kenji Hata et al., Science 306 (2004) pp.1362)

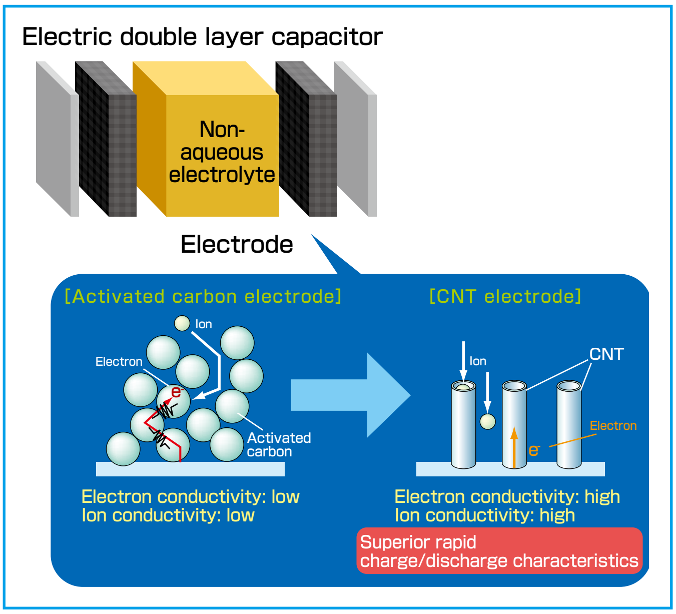


Figure 2. Comparison of activated electrode and CNT electrode

Lithium ion secondary battery utilizing nanostructures

With the progress in electric vehicles and mobile electronic products such as cell phones, increasingly high energy capacity and high power are demanded of lithium ion secondary batteries. In response to such demands, we have been attempting to apply active materials possessing nanostructures to the electrode of the lithium ion secondary battery.

Enhanced energy capacity and high power through increased surface area

When materials are made smaller to sizes in the nano-order, they exhibit properties differing from those of their bulk form. The same result has been also observed when applying nanosize active materials to the electrode of the lithium ion secondary battery. For example, it had been known that insertion/extraction of the lithium ion into/from anatase type titanium dioxide (TiO_2) is possible, but insertion/extraction of the lithium ion into/from the rutile type TiO_2 is nearly impossible. However, if the size of the rutile type TiO_2 becomes as small as 15 nm, insertion/extraction of the lithium ion becomes possible, and the charge/discharge capacity reaches as high as 365 mAh/g. Further, regarding anatase type TiO_2 as well, the theoretical capacity in bulk is about 167 mAh/g, but in nanoparticles of 6 nm, the charge/discharge capacity increases to 360 mAh/g. In this way, even conventional active materials show significant increases in charge/discharge capacity when made smaller to the nanosize, owing to the effect of increased surface area.

Enhanced performance due to increased surface area is also apparent in the power characteristics. The 6 nm anatase type TiO_2 nanoparticle achieves a high charge/discharge capacity of 240 mAh/g even at the high rate (rate = speed of charge/discharge) of 10A/g. Further, using the nanoporous crystalline TiO_2 which possesses the same high surface area as this nanoparticle, increased charge/discharge capacity and improved power characteristics (about 380 mAh/g at the low rate of 0.1 A/g, and about 260 mAh/g at the high rate of 10 Ah/g) have been observed. The improvement in power characteristics is enabled by the lithium ion and electrolyte being able to move easily into the nanopores (Figure 1). In the case of nanoparticles, likewise, there are nano-order pores between the particles.

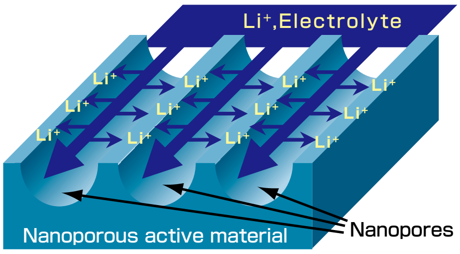


Figure 1. Image of diffusion path of lithium ions (Li^+) through nanopores of a nanoporous active material

Achieving further high power through construction of conductive paths

Oxidation-reduction by ions and electrons is involved in the charge and discharge of secondary batteries, not limited to lithium ion secondary batteries. In order to realize high power (charge/discharge in a short period of time), it is necessary to establish an efficient diffusion path for lithium ions to the active material, as well as an electronic conductive path for the electrons. Therefore, we have constructed a complex consisting of electrically conductive metal wire coated with an active material having a nanoporous structure, at a thickness of about several hundred nm. With the metal wire acting as the conductive path for electrons and the nanopores serving as the diffusion path for the lithium ions, each fulfills its own role (Figure 2).

In NiO/Ni systems, we have already achieved a charge/discharge capacity of about 800 mAh/g against the active material, even at the high rate of 10A/g. Presently, we are attempting to increase energy capacity and high power of the lithium ion battery by coating active materials possessing nanoporous structures on the surface of electrically conductive nanowires and nanotubes.

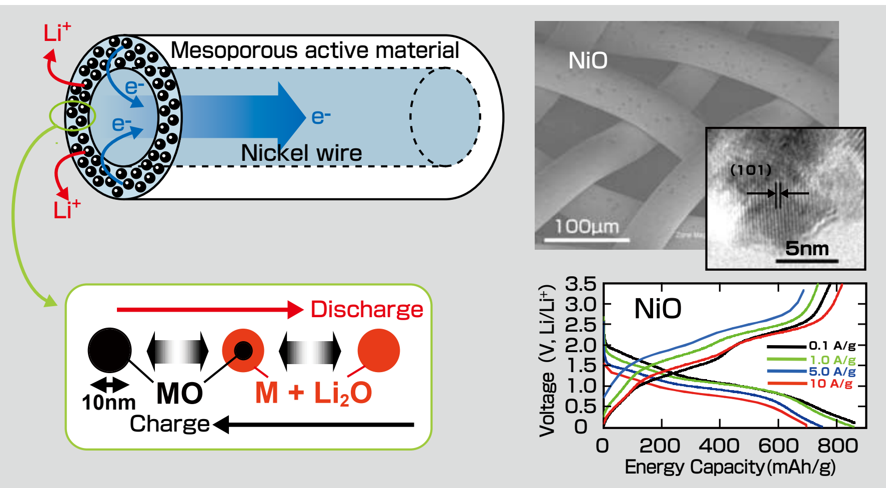


Figure 2. Achievement of both an electron conduction path and an ion diffusion path by structuring nanoporous active material on metal wire

Energy Technology Research Institute
Haoshen Zhou

Public Acceptance of Nanotechnology

From responsible research and development to innovation in nanotechnology

The challenge for a new methodology of technological development

The process of any new technology being accepted into society is accompanied by various obstacles and difficulties, no matter how superb the technology. Nanotechnology, for which high prospects are anticipated, is no exception, and its public acceptance is in fact making extremely slow progress.

What moral lessons have we learnt from our research and development in science and technology up to now and from the history of the public acceptance of such technologies, and how must we put these lessons to good use in the research and development of nanotechnology? The challenge of achieving a new methodology for technological development, which starts with considerations for societal impacts and public acceptance from the stages of research and development, is about to begin for nanotechnology.

Movements in research of the societal implication of nanotechnology

The U.S. government held its first workshop regarding societal implication in September, 2000, and since, has allocated roughly 10% of the nanotechnology budget to research regarding societal implication. A feature of this allocation is that it includes not only risk-related research, but also many development topics of core technologies whose public acceptance is not easy, reflecting the government's efforts to place emphasis on return of research and development investments as a result of the lesson learnt from the case of genetically modified organisms (GMOs). This basic stance is reflected in the systemization of functions in Woodrow Wilson International Center for Scholars (WWICS) for research of public acceptance of emerging technologies, as well as in programs such as the "Green nanotechnology Initiative" led by the Environmental Protection Agency (EPA).

EU as well, is undertaking comprehensive initiatives related to societal imlication, beginning with risk evaluation of nanoparticles. Further, of growing interest are efforts by the UK which is advancing its own public acceptance initiatives. In response to the report compiled by the Royal Society and the Royal Academy of Engineering in July, 2004, the British government established an inter-ministry collaborative system for research and policy formulation regarding the societal implication of nanotechnology in February of the following year. At the same time, it established frameworks for dialogue and debate in order to reflect public opinion in the system, and supports such activities in terms of funding as well.

Such initiatives regarding societal issues were slow to develop in Japan, owing to various reasons such as subconscious negative awarenesses, stemming from the misinterpretation that risk = Kiken (danger), that hampered development of risk-based discussions, and the negative effects remaining from the government's vertical administrative structure, of promotion-oriented factions rivaling restriction-oriented factions. The situation in Japan only began to change significantly from 2004.

From an open forum to a project

We have held open forums since August 5, 2004, with the objective of availing a place for information sharing in Japan regarding this issue and for creating a network. We have been working upon the basic stance of approaching both the risks and the benefits of nanotechnology, objectively and correctly. At the Keidanren hall on February 1, 2005, Japan's first comprehensive symposium regarding the societal impacts of nanotechnology was held, by AIST, the National Institute for Materials Science, the National Institute for Environmental Studies, and the National Institute of Health Sciences of the Ministry of Health, Labour and Welfare, and backed by relevant ministries.

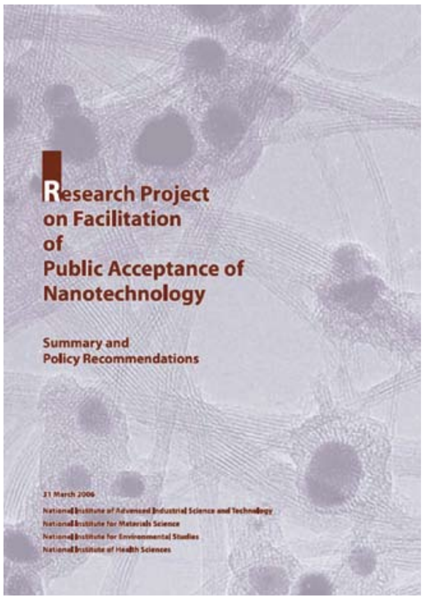


Photo 1. Summary and Policy Recommendations on Public Acceptance of Nanotechnology

The framework of coordination between these four public research institutes is carried on in "Research Project on Facilitation of Public Acceptance of Nanotechnology," a project in the FY2005 Project for Special Coordination Funds for Promoting Science and Technology of the Ministry of Education, Culture, Sports, Science and Technology. In the project, 70 participants conducted investigations aiming to make policy recommendations regarding issues such as risk management, environmental impact, health impact, and ethical/social issues. On February 1, 2006, the international symposium "Exploring the Small World: Role of Public Research Institutes" was held, and the results of investigative research by the project were reported.

The policy proposals compiled by the project regarding responsible research and development of nanotechnology were reflected in the strategies for the field of nanotechnology/materials in Japan's Third Science and Technology Basic Plan for 2006-2010 by the Council for Science and Technology Policy. Specifically, standardization of nanotechnology, risk control measures, outreach activities, literacy enhancement, and education/

human resources development are indicated, among others, as the issues to be tackled by various ministries. An example of materialization of the above is the launch of activities of the NEDO-sponsored new research and development project "Risk Assessment & Management of Manufactured Nanomaterialas" led by Dr. Junko Nakanishi, Director of the Research Center for Chemical Risk Management at AIST.

Turning social issues into a driving force for creation of innovation

In 2005, the year we launched the project mentioned above, AIST also launched projects for risk management of nanoparticles and standardization of nanotechnology. The prompt actions taken by AIST in response to expectations of private-sector corporations and the government since then have evolved significantly, and AIST has already become a global leader regarding social acceptance of nanotechnology.

Attempts to position the issues, such as societal impact and public acceptance encompassing risk management and standardization, in the stages of research and development constitute an original research and development strategy of AIST, aimed at creation of innovation from core technologies. At the same time, AIST is expected to generate large outcomes which are required in the runup to full scale development of nanotechnology. These include the streamlining of various relevant laws, industrial standardization, and development of social platforms including risk governance. Consideration for the issues such as standardization and risk management during the process of core technology development is truly the driving force behind the creation of innovation from AIST.

Responsible research and development and public acceptance

From June 26 to 28, 2006, at the Gakushikaikan, we held the Second International Dialogue on Responsible Research and Development of Nanotechnology, in which about 90 participants gathered from 21 countries as well as Taiwan and EU, to carry out discussions regarding the following five topics: environment health and safety issues, ethical legal and societal issues, education and capacity building, developing country issues, and nanotechnology standardization setting.

In the keynote lecture, AIST's President Hiroyuki Yoshikawa raised the point that it is important to maintain harmony instead of mutual exclusion in the maturation of both technology and society. The fundamental concept of this harmony is that we, the researchers, are required not to simply indicate the benefits offered by nanotechnology, but to form a societal consensus regarding the degree of the unavoidable risks that can be accepted, based upon a neutral assessment of risks and benefits. The responsibility of the researchers is to advance this assessment scientifically and link it to the research and development of core technologies, in order to implement responsible research and development. In doing so, we may lead core technologies, without imposing, to harmonious creation of innovation. This is what one of the participants described as "responsible innovation."

The future society opened up by nanotechnology

Not only does nanotechnology improve our lives by dramatically advancing existing technologies, but it constitutes a new technology that will also prove useful in resolving various issues facing society today, such as energy and food. However, looking at reality, according to statistics of the World Bank, we find that half of the world's population of 6.5 billion has no access to clean water and suffers poverty with no prospects for the future. In Japan as well, as we advance technological developments only prioritizing economics effects, we are seeing a widening of the social divide, the resulting strain of which is beginning to cause social instability.

In order to realize our common dream of a sustainable future society filled with the benefits of science and technology, we need to establish a new methodology for research and development of nanotechnology encompassing the perspective of social acceptance, and execute it responsibly as well as reform the awareness of researchers.

Technology Information Department
Masafumi Ata

Photo 2. The Second International Dialogue on Responsible Research and Development of Nanotechnology

Research and Development Support

Research and development support in nanotechnology

Promoting nanotech Japan

Nanotechnology, a technology in which substances are manipulated in a realm of a hundred thousandth of the thickness of a strand of hair, is on the verge of effecting drastic reforms, in the diverse fields including electronics, biotech, and environment/energy, that will leave its mark in human history.

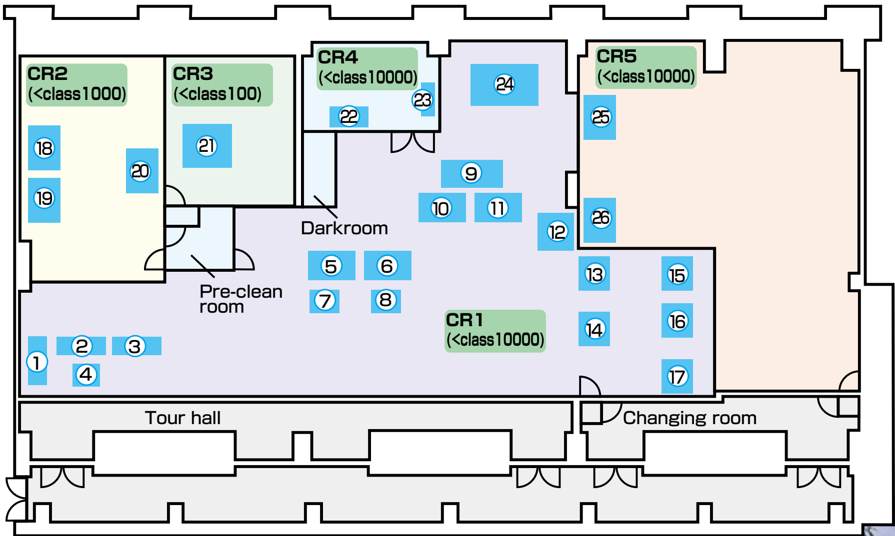
Handling of objects exceeding the human five senses inevitably requires grand and expensive equipment, which furthermore must be used in the clean environment of a clean room. Nanotechnology is a world based upon ideas. It is a dynamic and dream-filled area of research, where a little inspiration of a researcher can lead to great leaps forward. Although Japan's abilities in nanotechnology boast a high reputation worldwide, there are concerns that lack of equipment and facilities will become a barrier, and that even a good idea may become buried somewhere without ever seeing the light of day.

In order to draw forth the real strength of nanotech Japan, we need common-use open facilities for nanotech R&D which would allow anybody to use any equipment when needed, and as much as needed, to speedily try his/her ideas. Moreover, in order to enable these leading-edge technologies to blossom as industrial technologies, it is also essential to train on-site engineers who are knowledgeable in nanotechnology.

AIST Nano-Processing Facility

The Nanotechnology Research Institute has been keenly aware of such features of nanotechnology development since AIST's foundation in 2001, and has established the AIST Nano-Processing Facility (AIST-NPF) as a user facility for micro- and nano-fabrication/measurements, to be used by any qualified users. With the cooperation of other research units, we have opened the facilities to all researchers within AIST. In the USA, the National Nanofabrication Users Network (NNUN), the user facility network for nanofabrication, and its successor, the National Nanotechnology Infrastructure Network (NNIN), serve as the research infrastructures for universities and in addition are showing great performance in fostering nanotech venture businesses.

In 2002, aiming for a Japanese version NNUN, the Ministry of Education, Culture, Sports, Science and Technology launched the Nanotechnology Support Project. The Nanotechnology Research Institute and AIST-NPF, under the name of the Nano-Processing Partnership Program (NPPP), play a part in this Project as the managing organization of the Nano-Foundries Group (AIST, Waseda University, Tokyo Institute



Equipment layout in clean room (CR) and exterior of AIST Nano-Processing Facility (AIST-NPF)

1. Scanning probe microscope
2. Device parameter analyzer
3. Spectroscopic ellipsometer
4. Capacitance-voltage analyzer
5. Stylus step profiler
6. Wire bonder
7. Laser microscope
8. Optical microscope
9. Low vacuum scanning electron microscope
10. High resolution field emission scanning electron microscope
11. Focused ion beam system
12. Argon milling machine
13. Plasma asher
14. Multiple target sputtering system
15. Sputtering machine
16. Reactive ion etching machine (RIE)
17. Wafer oxidation furnace
18. Maskless arbitrary optical pattern generator
19. Electron beam writer
20. Electron beam writer
21. i-line stepper
22. Dicing saw
23. Ion milling system for TEM
24. Transmission electron microscope
25. ICP etching system
26. Vacuum evaporator

of Technology, Osaka University, and Hiroshima University).

NPPP avails over 30 different cutting-edge nanofabrication/measurement equipments – from electron beam writers to probe microscopes – to academic, business, and government researchers, free of charge, and provides nanofabrication services as requested by users as well. The system provides ten full-time staff members to respond speedily to equipment operation and technical consultations as well as fabrication requests. Anybody who is involved in nanotechnology research can apply for use from the NPPP home page. Presently, 130 external researchers from corporations and universities are registered as users and are utilizing NPPP to realize their ideas. We also hold over 100 tutorials for users on equipment usage each year (http://www.nanoworld.jp/nppp/).

Education and Training program

Regarding education and training program, in addition to initiatives within NPPP, we have been receiving support from the Industry and Academia Joint Project on Training Core Personnel for Manufacturing of the Ministry of Economy, Trade and Industry since 2005. In the application fields including intelligent home appliances, fuel cells, robots, medical instruments and biotech, in which Japan has a particularly strong competitive edge, we are working on developing the following training programs to cater to midsize enterprises which sustain the foundation as well as new creations in such industries: "Masters of basic processing skills/techniques and special element skills/techniques, who are capable of implementing sophistication of manufacturing technologies" and "Masters of nanofabrication process knowledge and of know-how for effectively utilizing state-of-the-art technology, who are capable of overseeing the skills/techniques of the manufacturing site."

We are working on fostering human resources with practical capabilities immediately applicable to medium and small companies, in cooperation with Waseda University, Ota City Industrial Promotion Organization, Technology Advanced Metropolitan Area (TAMA) Industrial Vitalization Association Inc., and Nanotechnology Business Creation Initiative. Focusing on technical fields of high versatility, such as electron beam lithography and surface nanofabrication, we are developing our own original instructional materials which balance principle with practice, with the objective of further enhancing practical workability in the classroom lectures and NPF trainings, while also internships at companies (http://www.seed-nt.jp/).

Nanotechnology Research Institute
Hiroshi Yokoyama

If you hope to create a future business using cutting-edge nanofabrication technology

Are you thinking, "I'm interested in nanofabrication technology, but I won't be employing it for a long while yet…"? Already, individuals from various industries are participating in the curriculum of AIST's "Training Program of Supervising Engineer for Nano-Tech Manufacturing (SEED)" to acquire the skills for unfolding new businesses using nanofabrication techniques, or for promoting sophisticated technical coordination with business partners.

This curriculum is not a unilateral communication of information from the lecturer, but consists of bilateral type training in which the contents can be customized to resolve various bottleneck issues at the original workplace of the trainees.

We also offer training menus catered to those using the curriculum to gain knowledge required in sales activity.

Of course, signing of a confidentiality agreement with the company at the site of internship is possible as required. Without any knowledge of nanofabrication technology, you will have no idea of when you should acquire the technology. We are awaiting your inquiries.

● Contact information
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E-mail: seed-info@m.aist.go.jp
Online Application: http://www.seed-nt.jp/

Lecture and training scenes

Project Administration

Project administration for the Nanotechnology Program and NEDO projects

The objective of the Nanotechnology Program which was launched in FY2001 is to further strengthen the competitive edge of industries by building the platform technologies for nanotechnology −a technology that will bring about revolutionary progress in various industrial fields including information and communications, environment, energy, and medical care− and to develop them into industrial technologies.

The Nanotechnology Program consists of five areas, including materials (Nanomaterials and Processing Technology) and basis for promotion of nanotechnology and materials. NEDO, under the Nanotechnology Program, executes specific project administration work. The Nanotechnology and Materials Technology Development Department, as of FY2006, is currently in charge of six projects in the materials area (Nanomaterials and Processing Technology), two projects in the area of basis for promotion of nanotechnology and materials, and one development effort in nanotechnology practical application (see Figure for details).

Of these, the “Research and Development of Nanodevices for Practical Utilization of Nanotechnology” project, since FY2005, has been aiming to realize speedy R&D and application by implementing narrowing down of candidates by stage gate process as well as research and development through cross-industrial and vertical collaborations. In light of the fact that many promising cases were submitted for it in FY2005, the project was scaled up drastically to a priority project for FY2006, and is based upon six innovative nanotech key technologies (self-organization/self assembly, thin film formation technology, nanoimprinting technology, single atom/molecule manipulation technology, nanospacing technology, and nanofiber technology).

In addition, our Department implements a project of sample matching in parallel with research and development projects, with the objective of disseminating the outcomes obtained in research and development up to now. In this project, intended for samples of NEDO project outcomes, we actively implement external transmission of the outcomes as well as promote matching to allow companies which possess proposals for usage development, practical application, or product realization, to assess the feasibility of their ideas. Through these efforts, we hope to enable the seeds of developing technologies to be put to early practical use.

In our Department, nine projects were completed in FY2005, and they will be held up for ex post evaluation this fiscal year. We are also expecting completion of additional four projects in FY2006. We are investigating the possibilities to support practical application of the outcomes of completed projects through sample matching and such. At the same time, regarding projects to be newly launched, we will continue on with resourceful and diligent efforts by constantly being aware of movements in the industry, embracing such opinions, and reflecting them in a technological strategy map, in order to definitely link the buds of basic technologies to practical application.

New Energy and Industrial Technology
Development Organization (NEDO)
Hironobu Teramoto

Project	H12	H13	H14	H15	H16	H17	H18	H19
Nanotechnology Glass Project	3.0	4.9	5.3	4.1	3.7	3.5		
Synthetic Nano-Function Materials Project		2.1	3.2	2.5	2.8	2.3		
Nanotechnology Particle Project		8.0	8.2	5.7	5.8	5.2		
Advanced Nanocarbon Application Project (F21)			7.1	11.8	11.3	10.2		
High-Strength Nanotechnology Glass Project for Displays (F21)				0.1	3.9	1.7		
Highly Functional Nanotechnology Glass Project for Photonic Devices (F21)				2.6	2.3	2.2		
Carbon Nanotube FED Project (F21)				6.7	9.3	8.0		
Advanced Diamond Technology Project (F21)				7.1	7.2	6.7		
Full Color Rewritable Paper Using Functional Capsules Project (F21)				5.3	4.3	3.6		
Nanostructure Coating Project (Materials Technology, Nano Material Process Technology)		4.5	4.8	3.4	3.4	3.1	3.4	
Nanotechnology Metal Project (Materials Technology, Nano Material Process Technology)			5.8	4.7	3.9	3.0	2.4	
R&D of 3D Nanoscale Certified Reference Materials Project			3.4	2.4	5.2	3.1	2.9	
High-Efficiency Ultraviolet Semiconductor Emitter Project (Materials Technology, Nano Material Process Technology)					3.5	3.3	3.3	
Project on Nanostructured Polymeric Materials (Materials Technology, Nano Material Process Technology)		11.6	10.8	8.8	8.0	6.3	6.6	
Nanotechnology Material Metrology Project		1.9	2.0	1.5	1.5	2.1	2.7	
Research and Development of Nanodevices for Practical Utilization of Nanotechnology (Nanotech Challenge Program)						7.6	23.3	
Carbon Nanotube Capacitor Development Project (Materials Technology, Nano Material Process Technology)							2.9	
High-efficiency Processing Technology for Three-dimensional Optical Devices (Materials Technology, Nano Material Process Technology)							3.9	

Figure. Research and development period of of Nanotechnology Program, and their budget scale (100 million yen)
(charged by NEDO Nanotechnology and Materials Technology Development Department)

Project introduction

R&D of 3D Nanoscale Certified Reference Materials Project

Metrology Institute of Japan
Isao Kojima

Supply of the world's smallest SI-traceable 100 nm pitch nanoscale based upon Japan's Measurement Law (JCSS system) is about to begin.

The speed of miniaturization of semiconductor devices is ever-increasing. Already, a plant has emerged which is capable of manufacturing in the minimum size of 65 nm (half pitch). The most important element in the testing, measurement, and control of this size of semiconductor device is the metrological electron microscope, called the critical dimension-scanning electron microscope (CD-SEM). And what is required in maintaining the measurement precision of this CD-SEM is a 'ruler' in the nanometer realm. For the fabrication of devices beyond the size of 65 nm, an accurate 'ruler' scaled at a pitch of about 100 nm is indispensable, to replace the present 240 nm pitch microscale. Further, in order to enable Japanese industrial products to survive international competition, actualization of a 'ruler' traceable to a national standard was urgently needed. This 'ruler' will likely be utilized up to the 45 nm generation.

Calibration services in the 100 nm pitch are performed by Japan Quality Assurance Organization (JQA), as a JCSS-certified organization. The technique developed for this calibration uses a laser having wavelength of an unprecedented shortness of 193 nm as the light source for diffraction, thereby enabling calibration to a pitch of 100 nm, which is about half of this wavelength. The diffraction angle required in the process of calibrating the scale of the 'ruler' is measured using a rotary encoder calibrated by national standard, and the light source wavelength is calibrated against a national standard using a newly developed device for wavelength calibration by pulse laser interferometry, making the values imparted to the scale completely traceable to international units. Furthermore, with completion of international comparisons by the International Committee of Weights and Measures (CIPM) in sight, this newly developed 100 nm pitch 'ruler' will be available for use anywhere in the world, as an ultra-precise and accurate 'ruler.' An annual 300-400 calibrations are expected to be conducted.

Major outcomes have already been obtained in developments in the depth-direction scale as well. Here, we have installed a technique for self-calibration in the rotary encoder which controls the angle scanning of the goniometer, in order to realize SI traceability of the X-ray reflectivity device. Using it, angular precision was improved ten-fold, and the accuracy of film-thickness measurement was narrowed to10^{-3} nm. Not limited to the above, its applications show ground-breaking possibilities for ultra-high-precision X-ray diffraction measurement and are thus commanding high anticipation from sophisticated synchrotron radiation facilities such as SPring 8. Its commercialization has already been achieved.

The example presented above constitutes an outcome of the 3D Nanoscale Certified Reference Materials Project, implemented through the cooperation of the Research Institute of Instrumentation Frontier under NEDO sponsorship. In the project, aiming for the ability to cater to miniaturization of semiconductor devices 10 years from now, we are developing a 'ruler' having basic structure of no more than 25 nm pitch in-plane and 10 nm in depth as a final target. In addition to this final target, we also establish, as topics for development, the supply to industry of the 'rulers' and related technologies required in the intermediate stages of the project. The outcomes discussed above are the two among our intermediate achievements which are worthy of special mention.

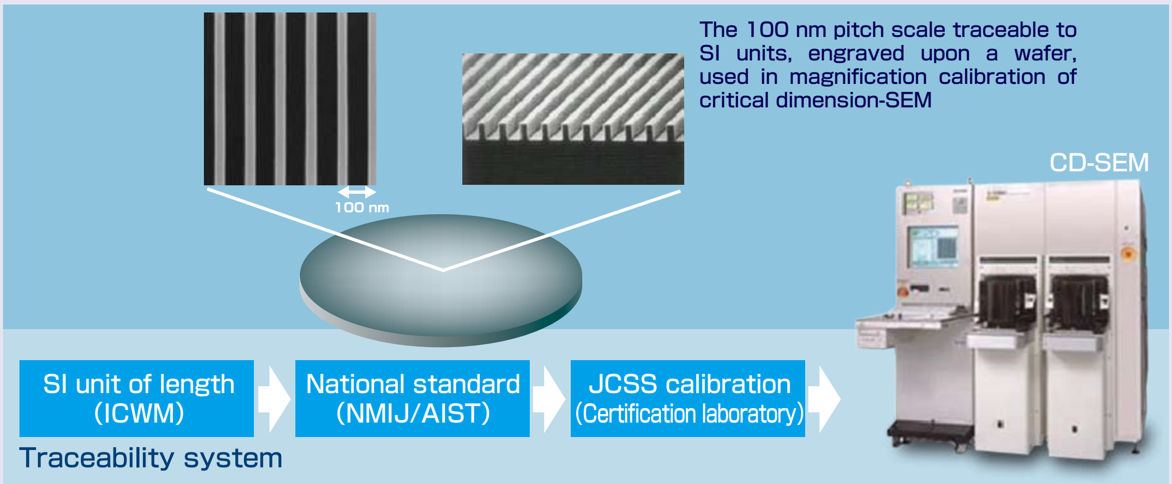

Figure. The 100 nm pitch nanoscale and the traceability system

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