NIMS NOW International

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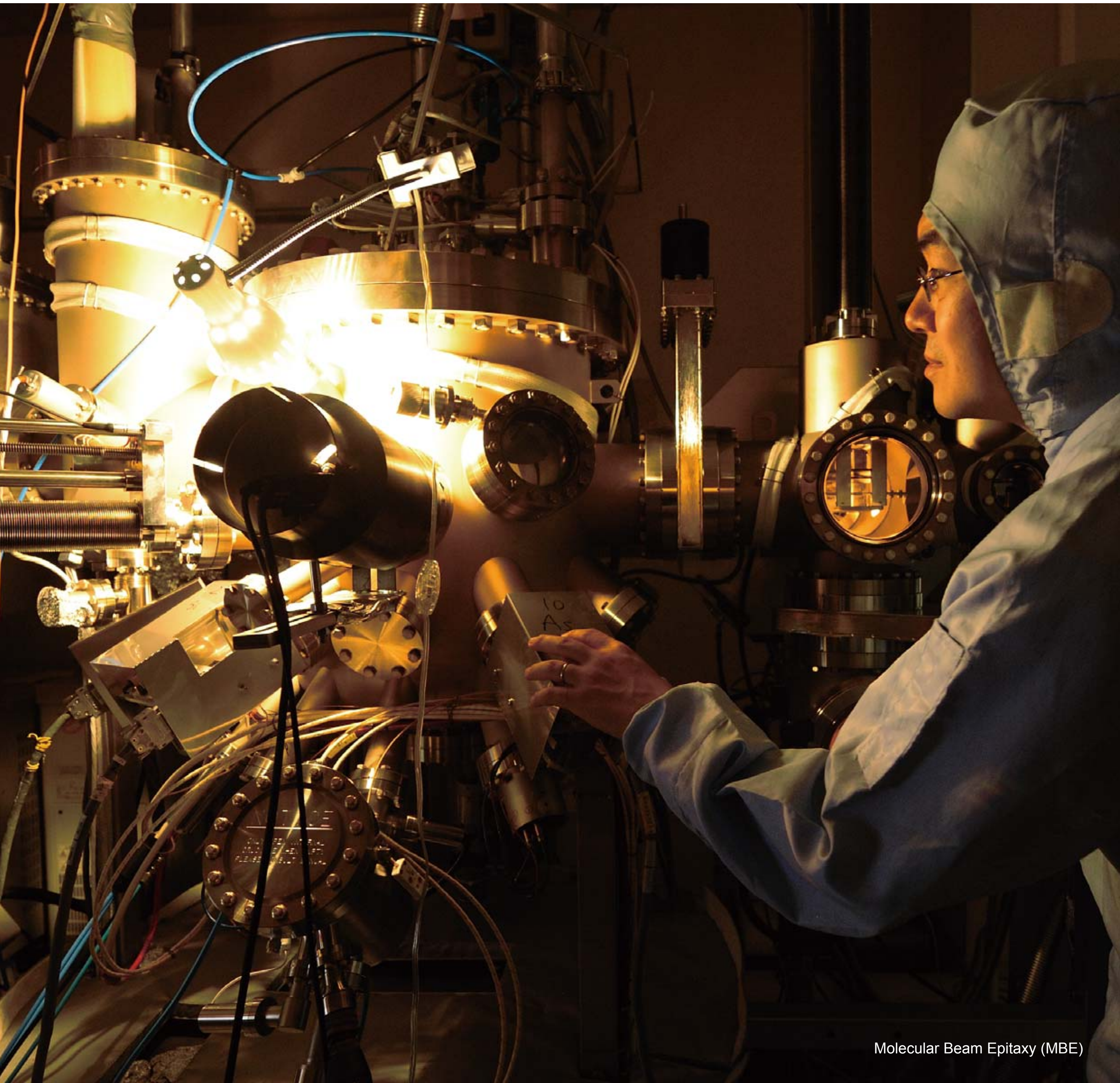
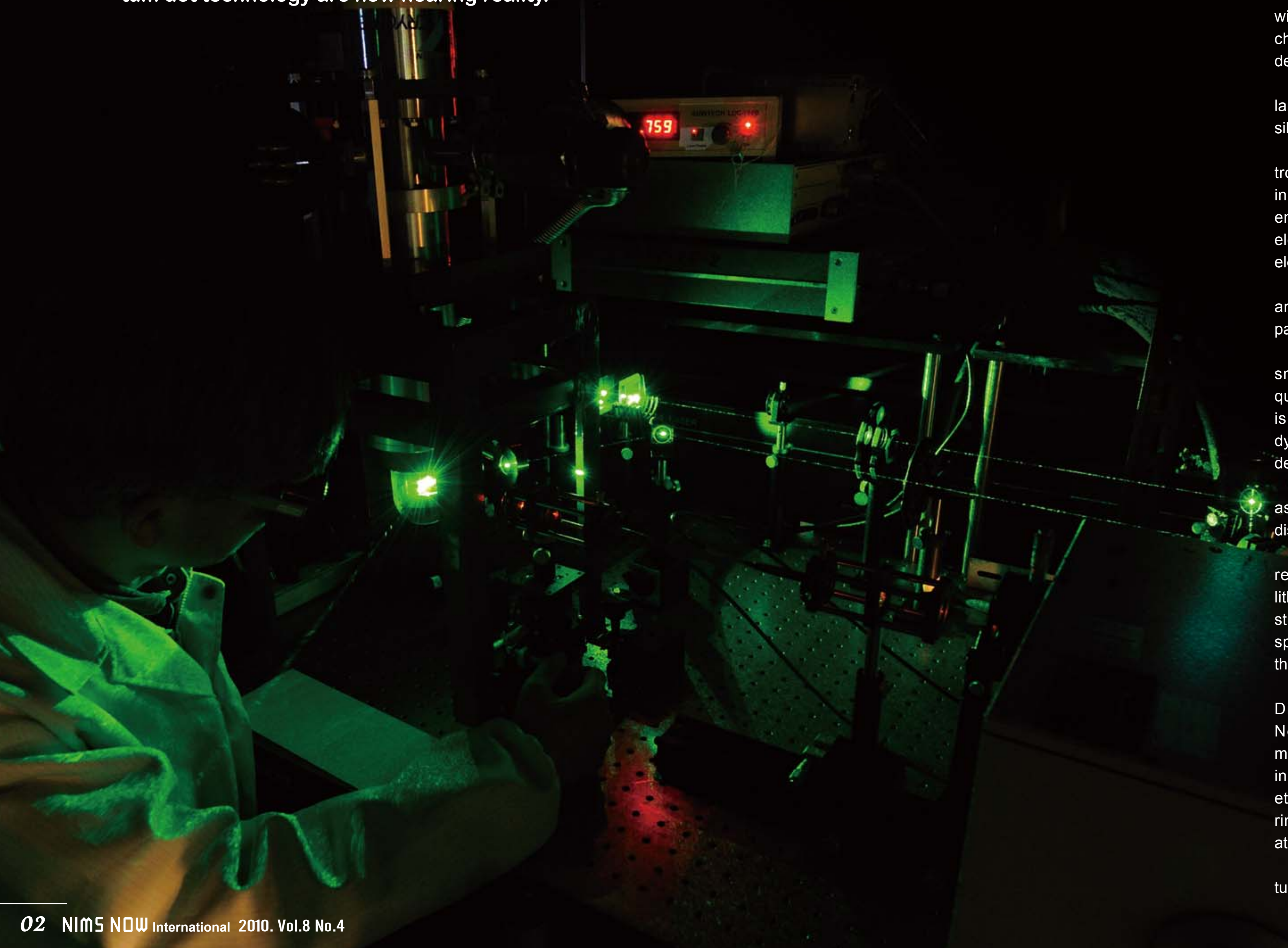
The Evolving World of Quantum Dots



Molecular Beam Epitaxy (MBE)

The Evolving World of Quantum Dots

Quantum dots. This dream technology, which was considered impossible to realize only 20 years ago, has made a dramatic leap into the realm of possibility and is now attracting keen attention. One front line in this rapidly-evolving field is the NIMS Quantum Dot Research Center, which is led by Managing Director Kazuaki Sakoda. In the near future, the research results achieved in this NIMS unit are expected to have an enormous impact on a diverse range of technologies, from lasers to photovoltaic cells, biotechnology, and quantum information analysis. What kind of technology is quantum dots, and what can this technology give to society? Breakthroughs in quantum dot technology are now nearing reality.



The Interest of Quantum Dots

– Variegated Physical Properties and Applications Realized by the Quantum Size Effect –

Kazuaki Sakoda, Managing Director
Quantum Dot Research Center

"Quantum dots" are actually nanometer-sized semiconductor microparticles. Because the wave function is confined within a small volume in this state, the energy level of the electrons takes discrete values. This is an extremely interesting phenomenon and results in diverse physical properties.

First, as the size of quantum dots becomes smaller and the wave function is confined within a smaller volume, the energy of the electrons increases in accordance with Heisenberg's uncertainty principle. This is called the "quantum size effect." As a result, even with quantum dots of the same material, it is possible to change the wavelength of the emitted light (i.e., color), depending on the size of the quantum dot (**Fig. 1**).

Second, because the luminescence peak is sharp, large optical amplification at the peak wavelength is possible.

Third, due to the Coulomb repulsion acting on electrons, the probability of multiple free electrons existing in a single quantum dot is small, which means that light emission and electrical conduction are realized by one electron. It is also possible to observe the spin of single electrons.

Fourth, the Coulomb attraction between electrons and holes is large, and excitons, which are composite particles of the two, are stabilized.

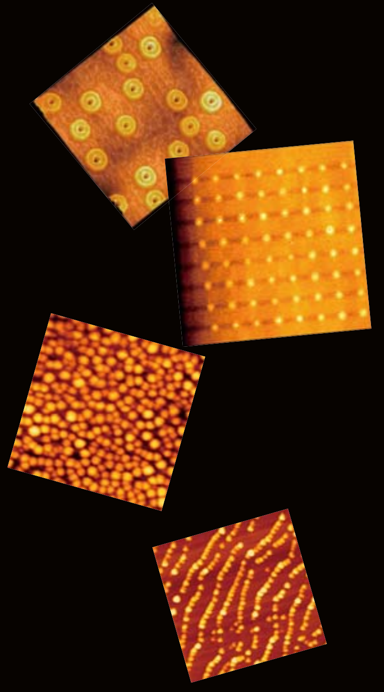
Fifth, because dephasing of the electrons is small, quantum dots are advantageous for realizing quantum computation, in which a long dephasing time is necessary. Furthermore, in comparison with organic dyes, quantum dots also have the advantage of minimal deterioration due to repeated light absorption.

Research aiming at a large number of applications, as shown in **Fig. 2**, is currently advancing, utilizing the distinctive features outline above.

In the initial phase of research on quantum dots, researchers attempted to fabricate quantum dots by lithography. However, because fabrication of such small structures is difficult and numerous defects occur on the specimen surface, the mainstream technique today is the self-organized growth method.

At NIMS, a group led by the previous Managing Director of the Quantum Dot Research Center, Dr. Nobuyuki Koguchi, developed the droplet epitaxy method (Koguchi method), and was the first to succeed in self-growth of quantum dots (1990). In 2005, Koguchi et al. also succeeded in fabrication of quantum double rings, in an achievement which attracted considerable attention.

This Special Feature introduces research on quantum dots at NIMS by the droplet epitaxy method.



(From top) Concentric double quantum ring, site-controlled quantum dots, extremely high density quantum dots, quantum dots arranged on a substrate with a stair-step shape.

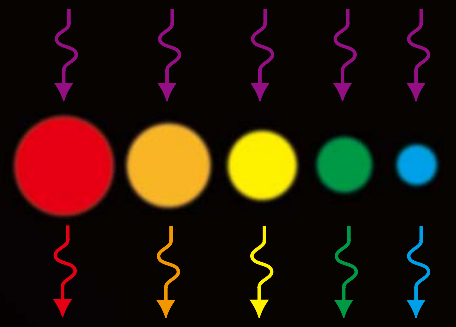


Fig.1 Change in color of emitted light due to the quantum size effect.

Photonics Field	Infrared sensors Displays
Quantum Information Field	Single photon light sources Quantum bits
Basic Science Field	Aharonov-Bohm effect Purcell effect
Biotechnology and Medicine Fields	Cell markers Cancer diagnosis
Energy Field	Quantum dot-sensitized photovoltaic cells Quantum dot type photovoltaic cells
Optoelectronics Field	Quantum dot lasers Quantum dot LEDs

Fig.2 Fields of application of quantum dots.

Quantum Dot Self-Assembled Growth Technology

Progress of the Droplet Epitaxy Method



Takaaki Mano
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Quantum dots created by self-assembled growth.

At present, the technique called “self-assembled growth” is widely used in the fabrication of quantum dots, which have a size of several 10nm. With this technique, nanometer-sized islands are formed naturally, simply by supplying the material uniformly to the surface of a substrate. These structures work as quantum dots.

This simple process enables fabrication of high quality quantum dots with an extremely high density of several 100 million to 100 billion per cm^2 **(Fig. 1)**.

The self-assembled growth method, which has these outstanding features, has developed greatly since the 1990s from the viewpoints of basic physical research on zero dimensional systems and application to devices such as lasers.

One well-known self-assembled growth method for quantum dots is the SK method (Stranski-Krastanov method). In the SK method, when a material with a lattice constant different from that of the substrate is grown, two-dimensional growth occurs first, followed by growth of three-dimensional islands due to lattice-mismatch. This method is used in the fabrication of indium-arsenide (InAs) quantum dots, which emit light at a wavelength suitable for application to optical fiber communications, and active efforts to realize practical application in quantum dot lasers and other devices are now underway.

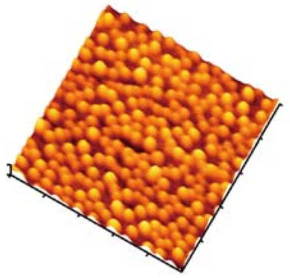

Fig.1 GaAs quantum dots produced by self-assembled growth by the droplet epitaxy method. Quantum dots with an extremely high density of 100 billion dots per square centimeter (~10^{11}/cm^2) have formed.

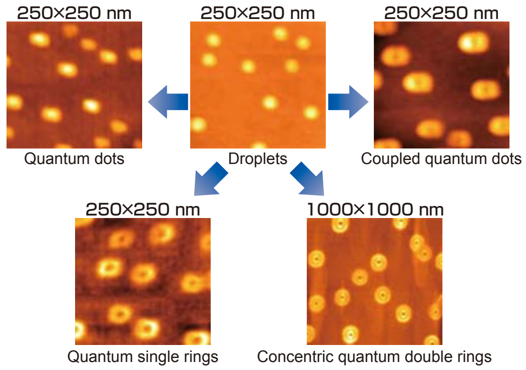

Fig.2 Ga droplets (upper row, center) formed by supplying only gallium (Ga) to a substrate, and quantum dots with diverse shapes formed by supplying arsenic (As) molecule beams with different intensities to the Ga droplets.

The “droplet epitaxy method” conceived at NIMS.

On the other hand, an original Japanese technique for self-assembled growth of quantum dots called the “droplet epitaxy” method was conceived at NIMS in 1990, and research and development have been ongoing up to the present.

This method is used for compound semiconductors, such as gallium arsenide (GaAs), the above-mentioned InAs, gallium antimonide (GaSb), and others, and utilizes nanometer-sized hemispherical metal droplets which are formed naturally when only gallium or indium is irradiated on the surface of a substrate **(Fig. 2)**.

The principle of this phenomenon is the same as that in which droplets form when water is sprinkled on a Teflon-coated frying pan. When arsenic (As) or antimony (Sb) is supplied, the droplets crystallize into a compound semiconductor, forming quantum dots.

Because the droplet epitaxy method is based on this growth mechanism, it has the feature of applicability to lattice-matched material systems such as gallium arsenide/aluminum gallium arsenide (GaAs/AlGaAs), which is not possible with the above-mentioned SK method.

Quantum dot growth in the droplet epitaxy method must be performed under conditions which are considerably different from those in ordinary crystal growth. For this reason, at the beginning of research and development, formation of high quality quantum dots was difficult due to various problems, including reduced quality in low temperature processes and the like. However, as a result of numerous improvements, such as the introduction of a heat treatment process, it has now become clear that extremely high quality quantum dots can be fabricated with good accuracy.

Furthermore, in addition to conventional quantum dots, researchers using the droplet epitaxy method have also succeeded in fabricating novel quantum dot structures with complex shapes that are difficult to realize by other methods, such as concentric quantum double rings, quantum single rings, coupled quantum dots, and others **(Fig. 2)** by paying attention to the complicated process of droplet crystallization.

The droplet epitaxy method – In the spotlight.

Current areas of research include the basic physics of these quantum dots and research envisioning application to quantum dot lasers, quantum dot photovoltaic cells, and other practical devices which take advantage of these distinctive features.

Our research to date has demonstrated the high utility and potential of the droplet epitaxy method, resulting in heightened interest in this method and a rapid increase in research groups following our efforts. Energetic research using the droplet epitaxy method is currently in progress in a number of countries in Europe, the United States, and Asia.

Precise Spectroscopic Experiments on Quantum Dots

Natural Atom and Quantum Dots – Similarities and Differencies


Takashi Kuroda
Quantum Dot Research Center
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Quantum dots that behave like atoms.

When quantum dots are fabricated using a semiconductor, the conduction electrons can be confined in a microscopic space with a size of several nanometers. This is similar to the quantum state of an isolated atom, that is, the state in which the electrons are restrained in the vicinity of the atomic nucleus. In the following experiment, it can be understood that quantum dots behave like atoms.

Fig. 1 shows the emission spectrum of the quantum dots which we fabricated. Because these quantum dots were fabricated by the self-organized growth method, a huge number of quantum dots, on the order of 10^9 to 10^{12}/cm^2, exist on the specimen.

In conventional fluorescence analysis, the emission signal from a large ensemble of quantum dots is measured (black line). In this case, a broad spectrum band can be observed, centering on the wavelength 730 nm.

On the other hand, if the specimen is placed under the micro-objective lens and the field of view is sufficiently small, it is possible to select a signal limited to a few numbers of quantum dots (blue and red lines). It was found that the emission spectrum at this time forms a collection of split lines, and is different from the spectrum from the quantum dot ensemble. The individual emission lines originate from carrier recombination in different quantum dots.

In general, the energy levels of solids form a broad continuous spectrum, known as the band structure. On the other hand, even though quantum dots are solids, they have discrete energy levels, similar to those of isolated atoms. These energy levels are determined by the electron confinement, thus depend on their size and shape. Therefore, unlike atoms, which have determined energies, it is possible to change the emission wavelength of quantum dots by controlling the shape parameters. As a disadvantage, when conducting experiments utilizing the quantum property and in serious device applications, this means that it is necessary to select single quantum dots.

Vivid reproduction of the quantum effect.

It is known that the energy levels of quantum dots consist of “shell structures” (*s* shell, *p* shell, etc.) like those of atoms. When one conduction electron exists in a quantum dot, that electron occupies the lowest-energy *s* shell. When the number of electrons increases to 2 or 3 electrons, those electrons successively occupy higher-energy shells, as in the arrangement of electrons in multi-electron atoms.

We conducted spectroscopic observations of single quantum dots with extremely high resolution, and discovered that the energy of multiple electrons in quantum dots is not simply the sum of the energies of the single-electron state, but deviates slightly from that value, reflecting the electron correlation. We also succeeded in observing the fine spectrum structure originating from the spin-spin interaction between electrons, and the super-fine structure originating from the electron-nuclear spin interaction.

Thus, a vivid reproduction of the quantum effects known in the world of atoms is possible by using quantum dots.

Furthermore, by controlling the size and shape of the quantum dots and the number of electrons contained therein, it is possible to investigate the fundamental nature of many-body effects, which is a central issue in solid state physics.

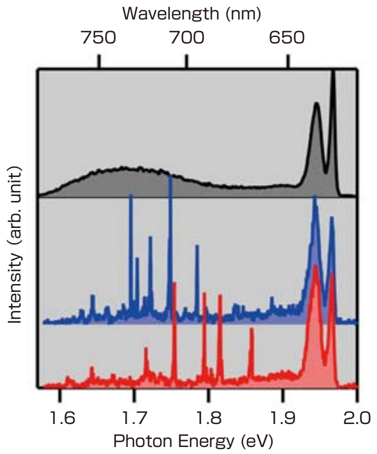

Fig.1 Emission spectrum of GaAs quantum dots. The black line shows the emission signal from an ensemble of quantum dots; the blue and red lines show the signals when the specimen was placed under a microscope and a limited number of quantum dots were selected. The signal around 1.95eV is the emission from the barrier layer, and the emission lines for the quantum dots are distributed centering on 1.7eV. The measurement temperature was 10K.

Fig.2 Photo of the NIMS micro-spectroscope. The specimen is placed between the glass windows of the vacuum cooler under the objective lens of the microscope in the foreground of the photo.

Development of New Light Source Using Quantum Dots

Toward Realization of Quantum Telecommunications


Takashi Kuroda
Quantum Dot Research Center
Marco Abbarchi
Quantum Dot Research Center

Telecommunication with single photon.

Ordinarily, laser light is used as the light source for optical fiber transmissions. On the other hand, quantum communication is a method in which the intensity of the light source is reduced, and information is transmitted at one photon per bit.

In conventional optical communications, one bit of information is given by one light pulse which consists of a huge number of photons. This meant that information could be stolen, without detection by the sender, by applying some type of device to the transmission line in order to extract a small number of these photon.

In contrast to this, when information is carried by individual photons, the light will not arrive at the intended recipient if there is even slight branching in the transmission line. Assuming someone attempts a wiretap, the theft of information can be detected. Thus, quantum telecommunications using single photons is a means of communication in which confidentiality is absolutely assured.

Semiconductor quantum dots generating a single photon source.

In order to realize quantum communications, a light source capable of generating single photons is necessary. A light source of this type is called a “single photon source.”

The single photon state can be realized in a quasi form if ordinary light, such as laser light, is adequately attenuated. However, in this case, the number of photons has a random probability distribution, and as a result, the transmission bit rate must be fatally reduced.

Semiconductor quantum dots have attracted attention as a single photon source alternative to this approach. If single quantum dots can be extracted, the light generated by these quantum dots will necessarily take the form of single photons, and it is possible to generate single photon pulses on demand simply by changing the timing of excitation.

Considering only the light intensity and spectrum, there is absolutely no difference between single photons and attenuated laser light. To demonstrate that this light consists actually of single photons we made an experiment shown in **Fig. 1**. Here, the light beam generated from the quantum dots is split into two parts with a translucent mirror, and the light in the respective routes is measured with a photon detector. Which route the photons will follow is probabilistic, and each photon detector counts the photons in a random time series.

Up to this point, the results are the same for a single photon beam and laser light. However, focusing on the events counted coincidentally by the two detectors, the coincidence count rate becomes zero in the case of the single photon beam (because one photon cannot be split into two or more photons). On the other hand, with attenuated laser light, the number of photons is not determined, and coincidence count events also occur with a certain probability.

Fig. 2 shows the results of an experiment with gallium arsenide (GaAs) quantum dots which we fabricated. It can be understood that the simultaneous photon count is zero in the light pulses detected at the same timing.

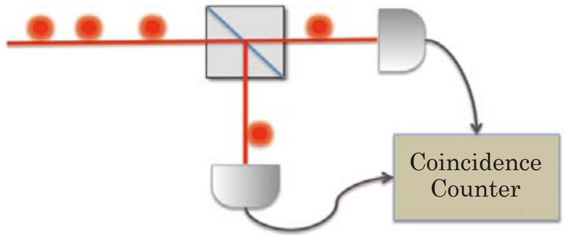

Fig.1 Arrangement of photon correlation measurement experiment. A beam splitter splits the light beam into two beams, which are irradiated on photon detectors. The coincidence counter counts the number of events when a photon arrives at two detectors simultaneously.

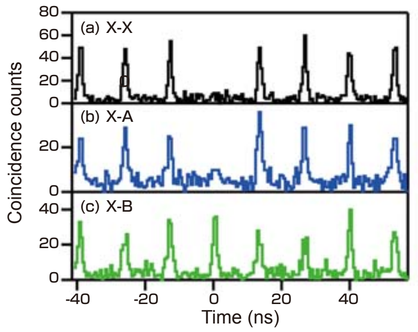

Fig.2 Single photon characteristics of GaAs quantum dots. The photon correlation was observed for pulse train-type emission signals from single quantum dots. The black line is the emission from electron-hole pairs when a quantum dot exists. It can be understood that there are no coincident count events at time 0. From this, it was concluded that only one photon exists in the light pulse. The blue and green lines show the emissions from multiple electrons when a quantum dots exists.

New discoveries by the materials science approach.

With research and development of single photon sources progressing in Japan, the United States, and Europe, we are arriving at important new discoveries by the materials science approach.

One new discovery was the use of a combination of gallium arsenide and aluminum gallium arsenide (GaAs/AlGaAs) as a quantum dot material. Although this had not been used in the past, we succeeded for the first time in generating single photons in the visible region by using this material. Because this generated wavelength coincides with the optimum wavelength of silicon photon detectors, which have high receiving sensitivity, high efficiency quantum communications can be realized.

On the other hand, in optical fiber transmissions, a light source with telecommunication wavelength band having reduced transmission loss has been desired. To meet this need, we succeeded for the first time in the world in generating single photons with a wavelength of 1.55 µm by using indium phosphide (InP) as the matrix material for quantum dots, and optimizing the shape of the quantum dots.

Integration of Quantum Dots and Photonic Crystals

Yoshimasa Sugimoto
Nano-Integration Facility,
Nanotechnology Innovation Center

Radiation field control using photonic crystals.

Control of the optical properties of substances by design of the radiation field (electromagnetic field) is one key technology in modern optics. Since the publication of a theory of photonic crystals by Yablonovitch and John in 1987, diverse types of photonic crystals have been devised and used for this purpose.

Photonic crystals are artificial structures in which the refractive index is spatially modulated at a period on the order of the wavelength of light, and make it possible to produce a frequency region in which electromagnetic waves do not exist (photonic bandgap).

Using this property, various types of hard-to-fabricate optical devices can be realized, such as wavelength filters, polarizing filters, optical waveguides, miniature optical resonators, and other devices with excellent features. In particular, one outstanding feature of slab-type photonic crystals, which are manufactured using semiconductor lithography technology, is the fact that formation of elaborate miniature structures is possible. This enables application to control of near-infrared light in the telecommunications band, among other uses.

Quantum dots and photonic crystals.

Photonic crystals of this type have a characteristic band structure and a strong dispersion property. On the other hand, semiconductor quantum dots have electrical and optical advantages originating from their high electronic density of state and low dimensional structure. Thus, high expectations are placed on devices which integrate photonic crystals and quantum dots in the field of quantum information systems and other future applications.

NIMS is the only materials research institute which possesses both quantum dot crystal growth technology using the droplet epitaxy method and slab-type photonic crystal fabrication technology using semiconductor ultra-fine processing technology. As such, NIMS is actively promoting research on the integration of quantum dots and photonic crystals.

Fabrication of a photonic crystalmicrocavity.

The Quantum Dot Research Center and the Nanotechnology Innovation Center are engaged in a joint study of photonic crystal microcavities, in which gallium arsenide (GaAs) quantum dots produced using the droplet epitaxy growth method are incorporated in a slab-type photonic crystal.

In the actual device, a single layer of GaAs quantum dots (quantum dot density: approx. 5x10^{9}cm^{-2}, 5K photoluminescence wavelength: approximately 760nm) are grown by the MBE (molecular beam epitaxy) method, and ultra-fine patterning is performed on the quantum dot growth substrate using a high precision electron beam lithography system with an accelerating voltage of 100kV (world’s highest level) and a high density plasma dry etching system to produce a photonic crystal microcavity structure. The result, as shown in **Fig. 1**, is an L3 type microcavity structure with a lattice constant of approximately 200nm, holes with radii of approximately 60nm, and no holes in the central area.

Confirmation of the Purcell effect.

The light emission properties of the photonic crystal microcavity fabricated as described above were observed by micro photoluminescence spectroscopy at a cryogenic temperature of 5K. From the emission spectrum, a sharp peak was observed as a result of light emission by the quantum dots coupled to the cavity mode of the photonic crystal. An intensity more than 20 times stronger and a spectral half band width of 0.3-1.5nm were obtained. Converted to the Q value, this is equivalent to 500-2000.

Furthermore, the emission life time was evaluated by time-correlated single photon counting using a picosecond pulse laser and streak camera, revealing that the emission life of the quantum dots in the microcavity is reduced by the Purcell effect during resonance (**Fig. 2**).

Future goals include improvement in the performance of this device to enable application as a single photon light source.

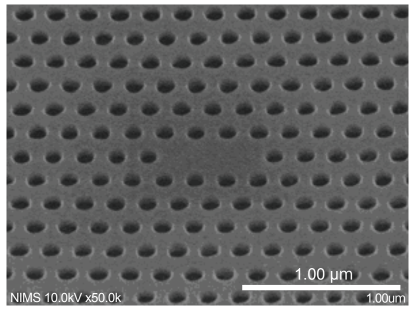

Fig.1 SEM image of the photonic crystal microcavity.

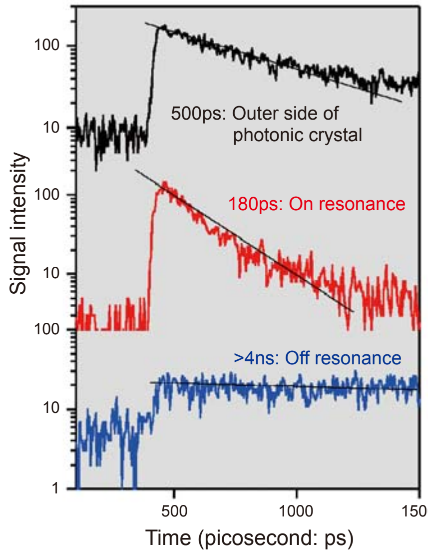

Fig.2 Emission life time by time-resolved photoluminescence measurement.

NIMS Quantum Dot Research – Attracting Worldwide Attention

Quantum Dot Research Center
Managing Director

Kazuaki Sakoda

NIMS is the birthplace of an original quantum dot manufacturing technology called the droplet epitaxy method. In addition to creating unique nanostructures, the NIMS Quantum Dot Research Center is also pressing ahead with convergent research with other fields and the development of more advanced analytical techniques. In this Face Interview, Dr. Kazuaki Sakoda, the Managing Director of the Quantum Dot Research Center, discusses how quantum dot research will evolve in the future and the role that NIMS will play in its development.

──When did you first become involved in quantum dot research?

After I completed graduate school, I worked for about 10 years in the research center of a private company, where I mainly did research on ultra-high density optical recording using photoreactive dye molecules. In the process of this research, I learned a number of things about the properties of organic molecules and related measurement methods.

Following this period, I was invited to Hokkaido University, and I encountered quantum dots. At the time, the main object of research was quantum dots of group II-VI semiconductors precipitated in glass, but I felt that the physical properties of quantum dots were extremely similar to those of the organic molecules that I had been working with until then. I instructed one graduate student, who was particularly good at laser spectroscopy, in the measurement methods that were already popular in the field of organic molecules. When we carried out measurements on quantum dots, we discovered that the value of the absorption linewidth which had been believed until then was completely mistaken. The correct value was as much as one order smaller.

──At that time, were you already considering applications of quantum dots?

I wasn't thinking about it at all. In fact, while I was at Hokkaido University, I was mainly involved in a different field, the photonic crystals. This was an emerging field at the time, and promising research topics were just waiting to be studied, both in experimental and theoretical research. However, because I was strongly attracted to theoretical research, I spent most of my time at Hokkaido University in theoretical work.

After enjoying about 10 years at Hokkaido University, I was invited to NIMS, and I became involved in research on quantum dots once again. The focus of my work is the creation of novel physical properties by combining photonic crystals and quantum dots. I'm doing my research in cooperation with the NIMS Nanotechnology Innovation Center in the preparation of specimens.

──The road to practical application isn't simple, is it?

In addition to the quantum dot laser, which has already been commercialized, people recently opened the way to practical application from a different direction, that is, use of quantum dots as cell markers. In fact, quantum dots can also be produced by chemical synthesis, and in the case of chemical synthesis, various functional groups can be fixed on the surface of the quantum dots. Taking advantage of this property, quantum dots can be used as a fluorescent marker by creating quantum dots to which cancer cells readily adhere. For example, real-time tracking of the movement of cancer cells in the bloodstream of mouse has now become possible.

──Could you tell us about methods of producing quantum dots?

One method is the self-organized growth method called droplet epitaxy, which was established at NIMS. This was announced by Dr. Nobuyuki Koguchi et al. in an oral presentation in 1990, and the first paper was published in 1991. Another one is the SK (Stranski-Krastanov) method. This method utilizes a phenomenon in which island-shaped structures are formed during the epitaxial growth of semiconductor thin films. Until recently, droplet epitaxy was a minority party, but because it has various outstanding features which are not possible with the SK method, including the fact that quantum dots with no internal stress and low anisotropy can be formed, the droplet epitaxy method is now being applied to light sources for quantum-encrypted communications. It is also possible to create quantum double rings by droplet epitaxy. In addition to the uniqueness of this structure, it can be applied to experiments in connection with the foundations of quantum mechanics, such as the Aharonov-Bohm effect. Given these circumstances, the number of papers on droplet epitaxy has increased rapidly during the last 2 to 3 years. Even though NIMS pioneered this technique, we have to keep busy to stay ahead of the competition.

──Finally, do you have any thoughts on young researchers?

We currently have 4 foreign graduate students in my laboratory, and I enjoy talking with all of these young scientists. On the other hand, I'm concerned that very few Japanese students are coming our way. Since we have allowances for research assistants, NIMS is an excellent environment for Japanese students who want to devote their full efforts to research. I hope that many young Japanese scientists will also join us.

Practical application of quantum dot lasers is just around the corner

Professor, The University of Tokyo
Director, Institute for Nano Quantum Information Electronics (Nano Quine)

Yasuhiko Arakawa

Professor Yasuhiko Arakawa of the University of Tokyo is one of the scientists who, together with Prof. Hiroyuki Sakaki, first proposed "quantum dots." Prof. Arakawa served as a member of the Executive Committee of nano tech 2010,[*] and is a leader and driving force in nanotechnology in Japan and the world. In particular, Prof. Arakawa has devoted much of his life to achieving practical application of the quantum dot laser. In this Special Interview, he offers insights on the present and future of quantum dots.

──Before turning to the subject of quantum dots, could I ask about your impressions of nano tech 2010?

I was impressed by the outstanding exhibition by NIMS. However, as a member of the Executive Committee, I think it was not good that none of the major electronics companies presented exhibits this year. In nanotechnology exhibitions, an awareness of the exit points for research, meaning practical applications, is particularly important. From this viewpoint, an overemphasis on basic materials strikes me as somewhat problematic. We're asking the electronics companies to return and participate again from next year.

On the other hand, we had active participation from other countries. On balance, I felt that the exhibits were in keeping with this event, as the world's No. 1 nanotechnology exhibition.

Likewise, although the exhibits were small in scale, the universities also made good efforts.

──Some feel that nanotechnology itself is at a turning point . . .

There was a kind of nanotech boom, which peaked around 2001. This was evident in the President's Nanotech Initiative in the United States and similar developments. However, nanotechnology is a basic infrastructural technology. For example, I feel that the fact that nanotechnology has been taken up in the government's 4 Primary Priority Areas, in parallel with the other 3 areas, is a little strange. Nanotechnology plays a role in supporting the other 3 areas, and can't really be separated out as one of the 4 areas. In this sense, I think the importance of nanotechnology will increase in the future. It's inconceivable that it might decrease.

Recently, there has been a lot of talk about exit strategies. However, rather than asking about the direct exit points for nanotechnology, I think that opening up more innovative exits, by use of nanotechnology in fields like IT and biotechnology, will become even more important.

──Now, let's talk about your quantum dots.

Because the quantum dot is a concept that was arrived at while searching for the ultimate form of a device, I naturally had thought about the exit.

In 1982, we published a general concept of quantum dots and suggested the possibility of the quantum dot laser. But that was a sort of thought experiment. We didn't think it would be actually possible in the 20th century. However, methods of producing quantum dots were discovered in the 1990s, and suddenly, the realization of this concept appeared to be feasible.

During the last 5 to 10 years, the quantum dot laser has swept the field of semiconductor lasers for use in optical local area networks.

──Will quantum dots replace other technologies the same way transistors replaced vacuum tubes?

It's a little different. It isn't a drastic change, like vacuum tubes being replaced by transistors. Externally, it looks the same, but because the internal active layer, that is, the part which emits light, consists of quantum dots, its performance is completely different. Because low energy consumption, low cost, stability against temperature changes, and other features can be achieved, quantum dots will replace the existing systems.

Although quantum dot technology is high tech, it is also a low cost technology. The key point is to popularize this technology in society by using high technology to produce low cost.

──What about expansion to a wider range of applications other than lasers?

At present, optical fiber amplifiers are mainly used, but these may be replaced by quantum dot amplifiers. Then, in the distant future, the quantum dot devices such as single photon sources will be in practice for quantum cryptography communication and quantum computer systems. Because quantum dots correspond to a specific wavelength and energy, early detection of cancers may be possible. Quantum dots also have the potential for production of photovoltaic cells with extremely high conversion efficiency.

──Finally, do you have any message for young researchers?

I think that talented young researchers are doing extremely good work. Although this is also due to the fact that budgets for research have become available recently, and there are ample situations where individuals can extend themselves, whether this easy access to funding is really a good thing for researchers is a delicate question. In these circumstances, information overload is also a problem, and researchers may unfortunately tend to focus on so-called priority topics. Truly innovative achievements are finally produced by concentrating on truly difficult problems with dedication and perseverance. I hope that young researchers will take on this kind of challenge.

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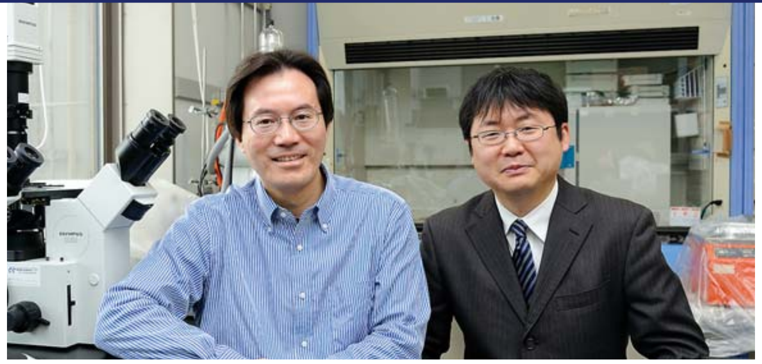
[*] nano tech 2010: International Nanotechnology Exhibition and Conference; for details, see the April Edition of NIMS NOW 2010.

Fabrication of Funnel-like Porous Scaffolds Using Ice Particulates as a Template

Biomaterials Promoting High Efficiency Tissue Regeneration

Naoki Kawazoe
Guoping Chen, Group Leader
Polymeric Biomaterials Group, Biomaterials Center



left: Dr. Chen, right: Dr. Kawazoe

Tissue engineering, which aims to regenerate tissues and organs that have been lost as a result of injury or disease, has attracted considerable attention in recent years. Porous scaffolds play an important role in tissue engineering, as they not only provide space for cells to be distributed in 3 dimensions to guide new tissue formation, but also control the shape and structure of the object tissue. Homogeneous cell distribution in the porous scaffolds is a key point to promote efficient tissue regeneration.

However, with the conventional porous scaffolds, it is difficult to secure a uniform cell distribution, and as a result, the regenerated tissues do not always meet the requirements. As causes of this problem, the surface pores are partially closed and the pore interconnectivity is not high enough. Precise control of porous structures of scaffolds is desirable.

In this study, we developed a new method to control the porous structures with completely open surface pores and well interconnected inner bulk pores by using ice particulates as a template **(Fig. 1)**. At first, micro water droplets are dispersed on a hydrophobic surface. Embossing ice particulates are formed by freezing these droplets. An aqueous solution of collagen or other polymers are allowed to flow into this mold, and then freezed at a controlled temperature. The ice particulates serve as nuclei to initiate the formation of ice crystals starting from their surfaces. Next, the ice is removed by freeze-drying, and a porous structure is formed. Following this, crosslinking is performed to make the scaffold insoluble and stable in water. With the porous scaffold obtained in this process, the surface pores are open and the inner bulk pores are well interconnected. Because the porous structure has a shape similar to a funnel, the scaffold is referred to as "funnel-like porous scaffold."

Scanning electron microscope observation confirmed the existence of surface large pores which reflect the shape of the ice particulates and well interconnected pores in the inner bulk **(Fig. 2, above)**. Furthermore, the surface large pores are connected to the inner bulk pores. The size and distribution density of the surface large pores depend on the size and distribution density of the ice particulates, while the size of the inner bulk pores depends on the freezing temperature.

As this example demonstrates, it was possible to precisely control the size and structure of the pores in the porous scaffold by using ice particulates. Cells seeded in this porous scaffold reached the inner bulk pores through the surface large pores and were uniformly distributed **(Fig. 2, bottom left)**. When bovine chondrocytes were cultured in the scaffold, cartilage-like tissue was regenerated **(Fig. 2, right)**. In the future, application to the regeneration of human cartilage is expected.

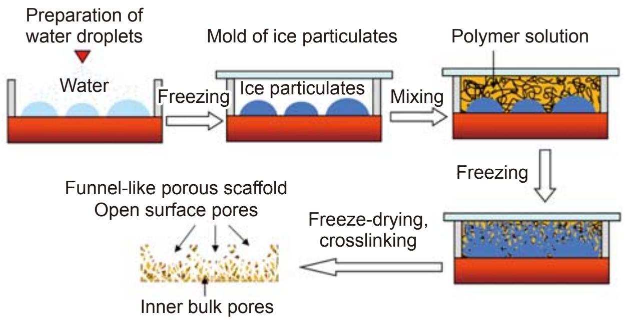


Fig.1 Preparation scheme of a funnel-like porous scaffold using ice particulates as a template. Ice crystals formed in an aqueous solution of a polymer link with the template ice particulates. A funnel-like porous structure can be obtained by utilizing this phenomenon.

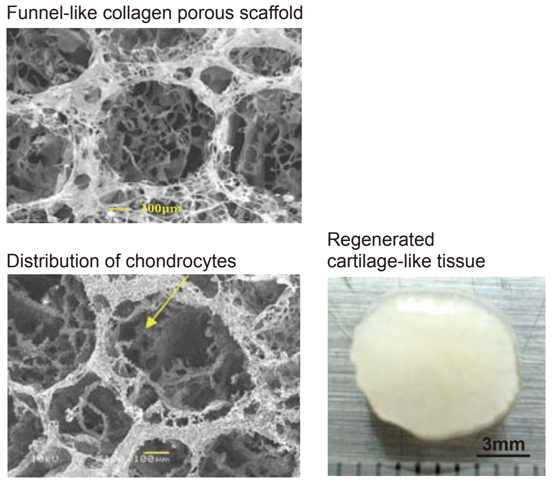


Fig.2 Regeneration of cartilage tissue using the funnel-like collagen porous scaffold. The photomicrograph on the bottom left shows cell distribution after 2 hours culture; the arrow indicates a cell. The photo at the right shows cartilage-like tissue regenerated after 3 weeks culture.

Development of High Performance Electrode for Fuel Cells

Toshiyuki Mori et al.
Nano Ionics Materials Group, Fuel Cell Materials Center

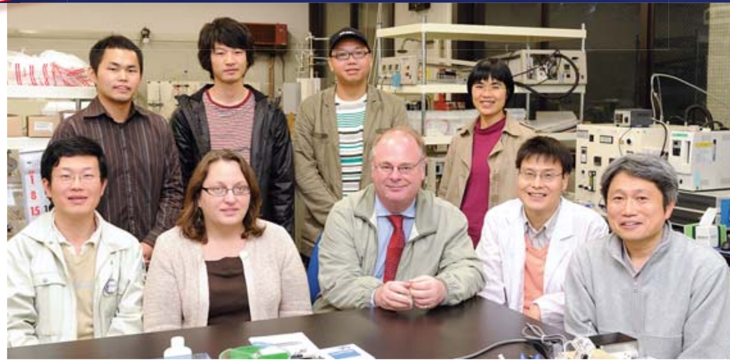


Photo: Dr. Mori (at far right) with researchers in joint research project.

Popularization of household fuel cells is being accelerated as one means of realizing a sweeping reduction in CO_2 emissions. In response to this trend, efforts to achieve higher performance in fuel cell electrode materials, and to reduce the amount of noble metals used in electrodes, have attracted much attention.

A fuel cell is a device which produces electricity utilizing the reverse reaction of electrolysis of water. The cathode in a fuel cell is an electrode which acts to produce water, together with protons ((H^+) ions) by reductive decomposition of oxygen molecules at the electrode surface. The anode is an electrode which changes water molecules to protons at its surface. These two electrodes are positioned on the two sides of the section containing dispersed ions, which are called the electrolyte. Achieving high performance in cathodes and anodes is an important issue for the development of fuel cell devices.

We are engaged in research and development on cathodes and anodes which provide higher performance than platinum (Pt) cathodes and the platinum-ruthenium (Pt-Ru) anodes, which have been the main types used until now, while also reducing consumption of these noble metals.

In order to create a material with high electrode activity not found in conventional metal electrodes, we are trying to fabricate a high activity interface, which does not exist in metal electrodes, by carefully designing the microstructure and structure around a hetero interface*1 of platinum and ceria (CeO_2), and to apply this material to fuel cells.

The accompanying figure shows the results of a comparison of the activity of cathode materials by measuring the current density in a sulfuric acid solution while supplying oxygen gas to the cathode surface.

In cathode materials for fuel cells, it is considered necessary to obtain a high current density in the oxygen decomposition reaction at the potential shown in the **Fig**.

The original NIMS Pt-Ru electrode showed extremely high cathodic activity compared to that of two other types of electrode, the commercial electrode manufactured by company A and company B.

A fuel cell using this cathode showed higher fuel cell output characteristics than those of fuel cells using commercially-available Pt cathodes.

Furthermore, the performance of noble metal electrodes is greatly reduced in ordinary environments where the electrode coexists with carbon monoxide (CO). By using an anode made of this platinum-ceria material, it was possible to achieve performance equal to that of commercial anodes, even when the amount of Pt was reduced to approximately 1/10 that of the commercial Pt-Ru alloy anodes. Thus, we also succeeded in developing an original NIMS anode material.

At present, in addition to making a careful analysis of the hetero interface of Pt and ceria using transmission electron microscopy (TEM) and photoemission spectroscopy, we are also working to develop electrode materials with even higher performance while calculating the band structure.

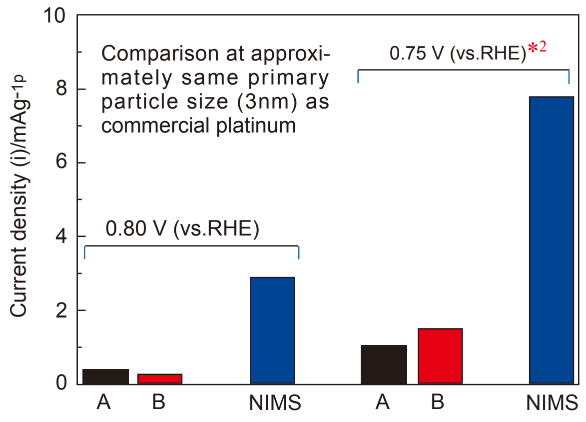


Fig. Comparison of commercial electrodes and NIMS electrode (rotary electrode; rotational speed: 3600rpm)

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[1] Hetero interface: Heterogeneous interface comprising metal and oxide materials.

[2] RHE: Reversible hydrogen electrode

NIMS NEWS

New Vice Presidents and Fellow of NIMS

NIMS has appointed new Vice Presidents and Fellow as below. Their terms are from April 1, 2010. The interviews with two new Vice Presidents will be on next issue of NIMS NOW.

Vice President
Junichi SONE

Doctor of Science. Graduated Department of Physic, Faculty of Science, Kyoto University. Completed Master course in Department of Physics, Graduate School of Science, Tokyo University. After serving as a Research staff at Central Research Laboratories and General Manager at Fundamental Research Laboratories of NEC, served as Vice President of Central Research Laboratories at NEC. Appointed as Vice President of NIMS from April 2010.

Vice President
Eiji MUROMACHI

Doctor of Science. Completed Master course in Department of Applied Chemistry, Graduate School of Engineering, Tohoku University. Served as Senior Researcher and Supervising Researcher at National Institute for Research in Inorganic Materials (NIRIM). After serving as Director of Superconducting Materials Center at NIMS and Deputy Director General at MANA, appointed as NIMS Fellow from April 2009. Appointed as Vice President of NIMS from April 2010.

Fellow
Yutaka Kagawa

Doctor of Engineering. Completed doctoral course at the Graduate School of Science and Engineering, Waseda University. After serving as Professor at Institute of Industrial Science, Graduate School of Engineering, and Center for Collaboration Research, the University of Tokyo, served as Professor at Research Center for Advanced Science and Technology of the University of Tokyo, and Coordinating Director at Materials Research for Reliability and Safety Field of NIMS. Appointed as NIMS Fellow from April 2010.

Basic Agreement on Mutual Cooperation by NIMS and Tsukuba City

(Apr. 1, 2010) NIMS and City of Tsukuba (Mayor: Kenichi Ichihara) concluded a Basic Agreement aiming at sustained development of a regional society which ensures an excellent living environment by securing the safety and security of residents, together with fusion of the results of research and development by NIMS and the policies of Tsukuba.

Under this agreement, NIMS and Tsukuba will promote cooperation in 6 areas. (1) use of mutual information, resources, research results, etc., (2) sharing of information in connection with the safety and security of city residents, (3) disaster prevention and environment preservation, (4) encouragement of science & technology and industry, (5) improvement of school education and social education, and (6) collaboration between universities and research institutes in Tsukuba.

Mr. Ichihara, Mayor of Tsukuba (left), and Prof. Ushioda, President of NIMS, (right) at the signing ceremony on Thursday, April 1.

Hello from NIMS

Even though my father and great-grandfather each lived in Japan for a couple of years, I didn't have a strong connection before joining NIMS. Initially, I came as a PhD Student for six months. The facilities and the level of research here are impressive. When given the opportunity, I applied to ICYS. I am grateful I was accepted. Since starting at ICYS-MANA, the staff made it easy to adjust to living here. My friends have helped me to feel comfortable and have taught me some about Japanese culture. During my two-and-a-half years here with ICYS, I've been able to enjoy the Japanese cuisine, ski on the Olympic slopes at Hakuba, climb to the top of Japan to greet the rising sun, visit historic Nikko, pound mochi, and swim in the clear blue Okinawan waters. This past March I made my connection to Japan more permanent with my marriage to my dear beautiful Shoko.

[Making mochi with friends]

Michael V. Lee
(USA)
ICYS-MANA Researcher
(September 2007 – present)

[Michael and Shoko Lee]

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