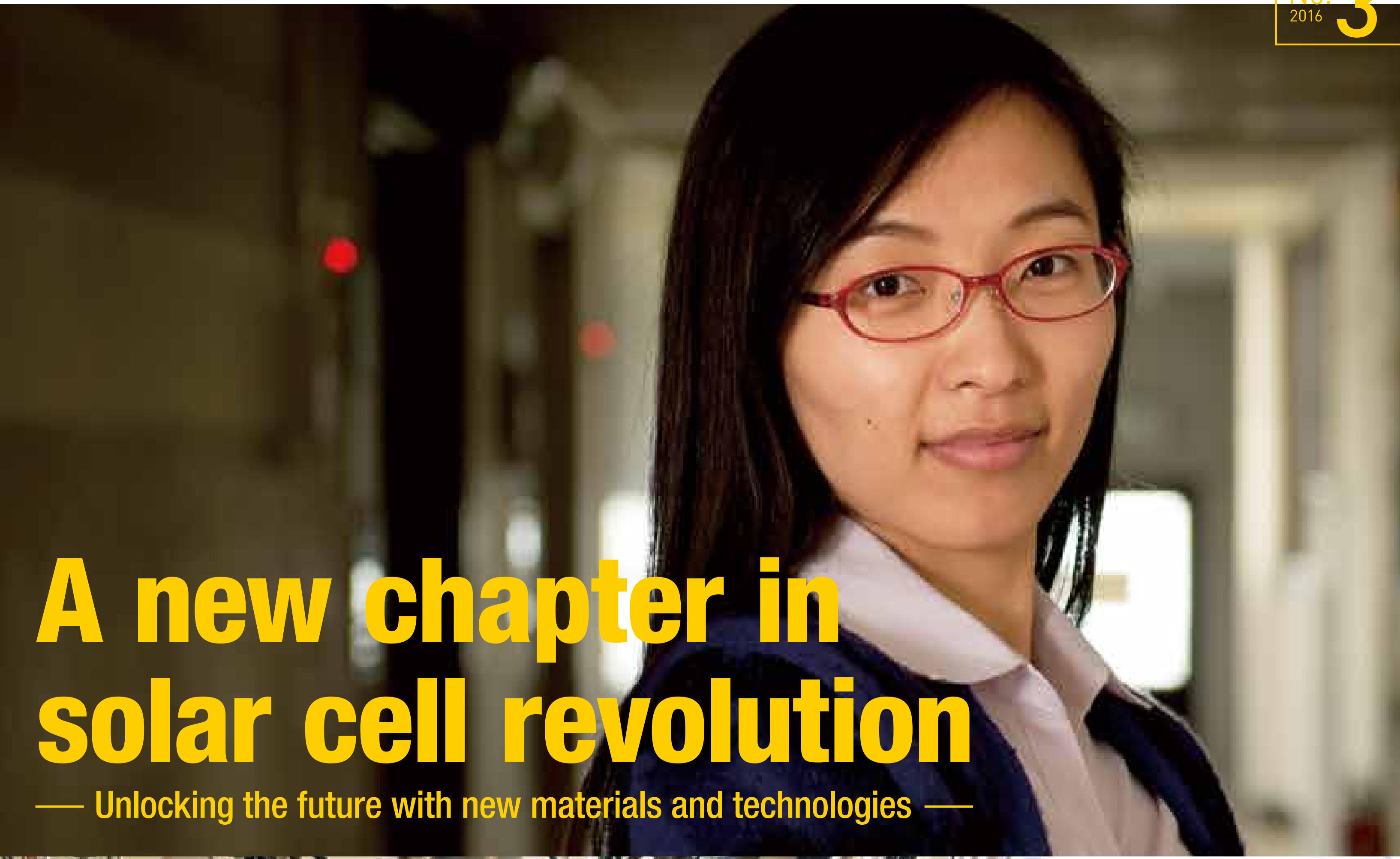
NATIONAL INSTITUTE FOR MATERIALS SCIENCE

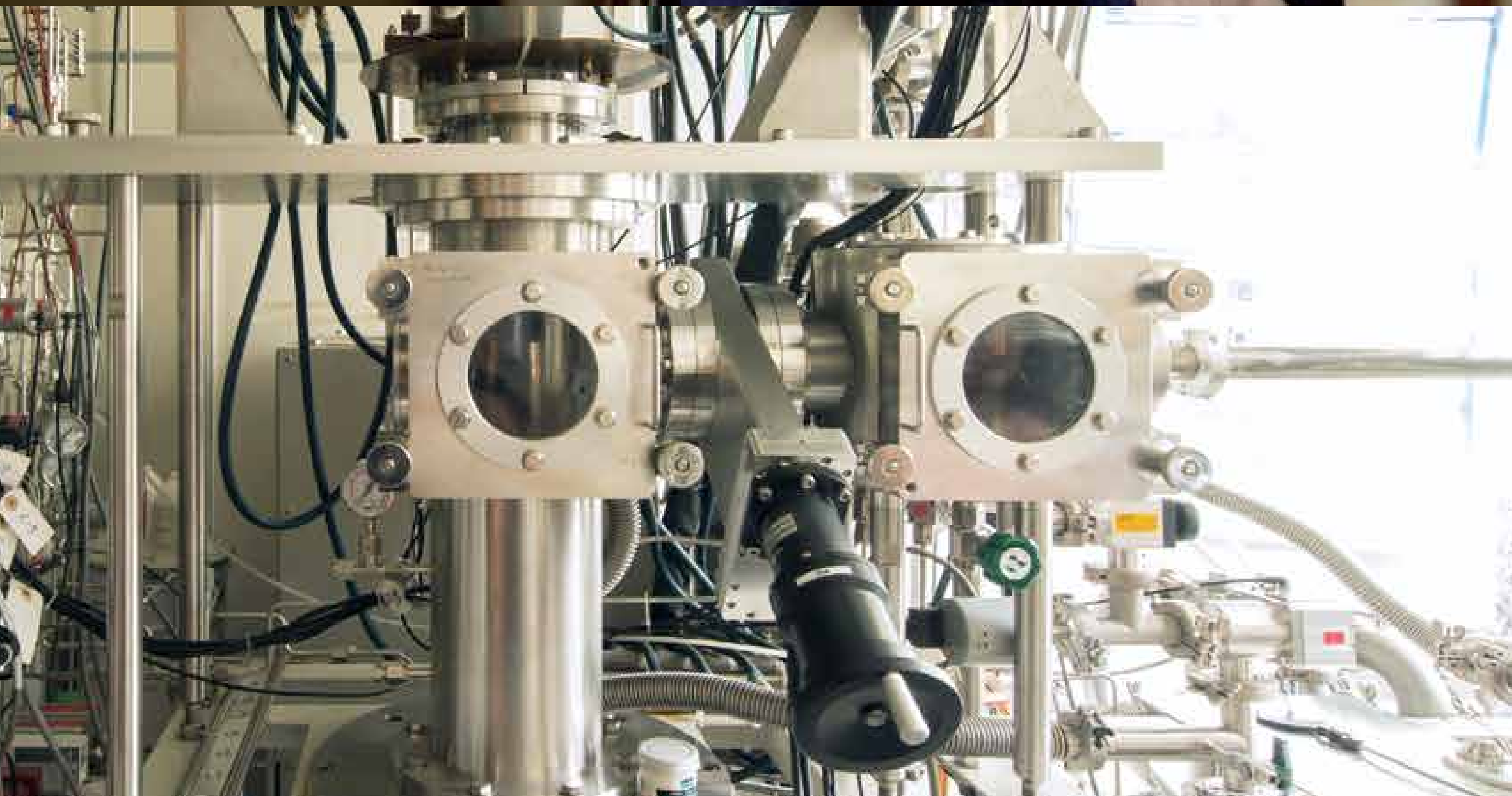
NIMS NOW INTERNATIONAL

No. 3 2016



A new chapter in solar cell revolution

— Unlocking the future with new materials and technologies —

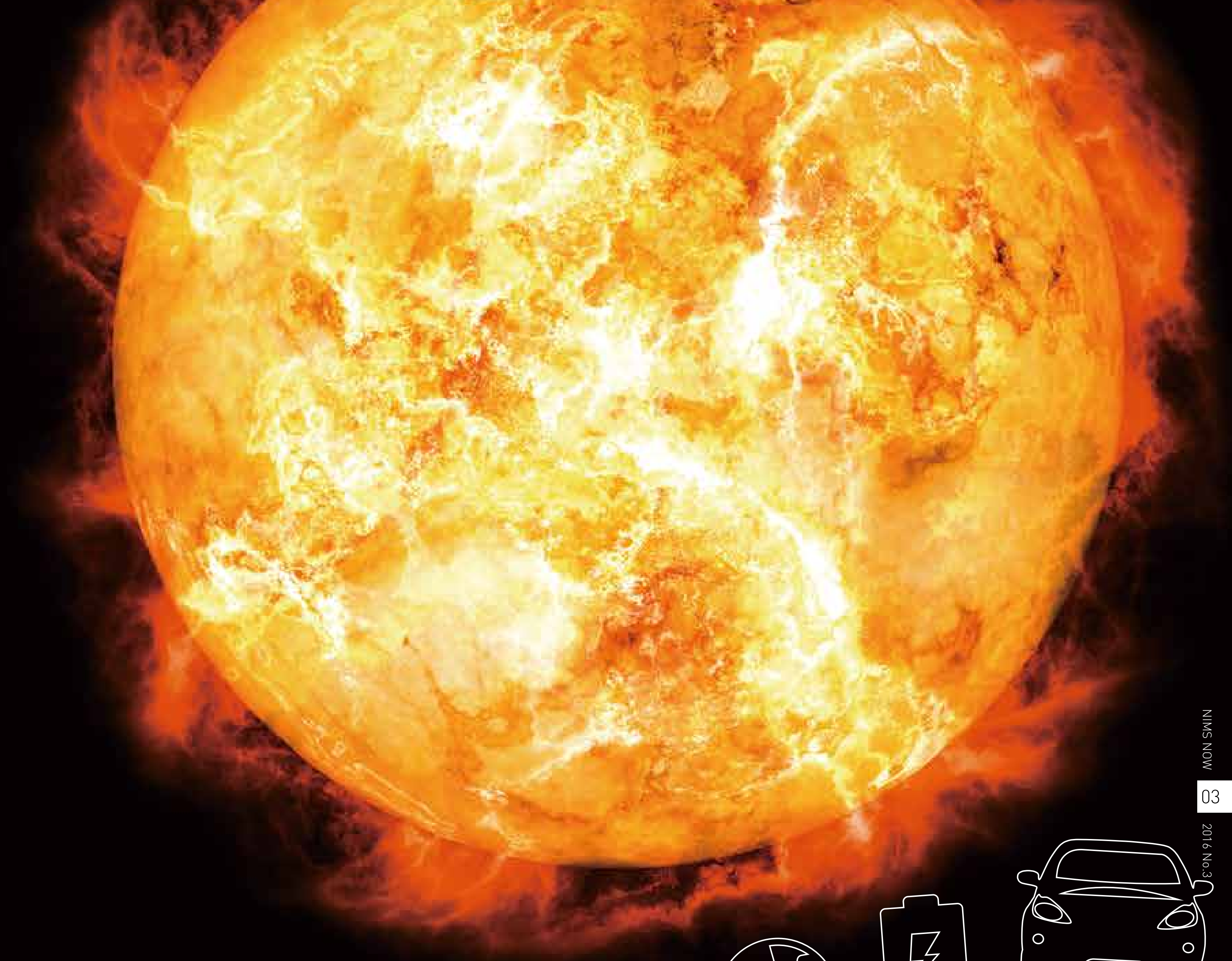


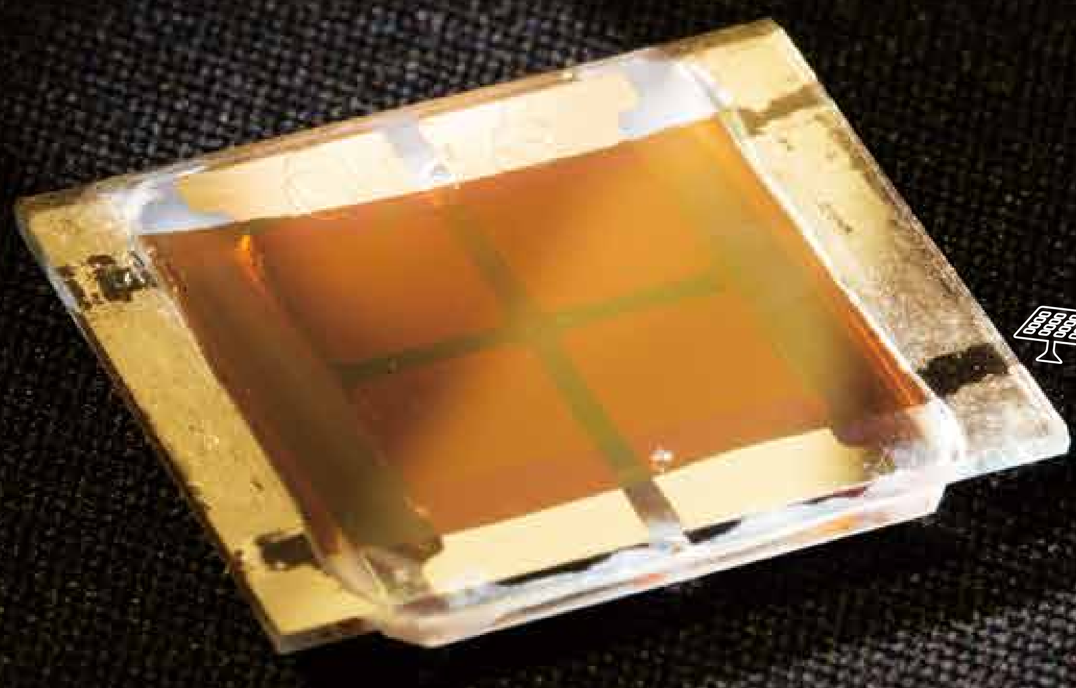
A new chapter in solar cell revolution

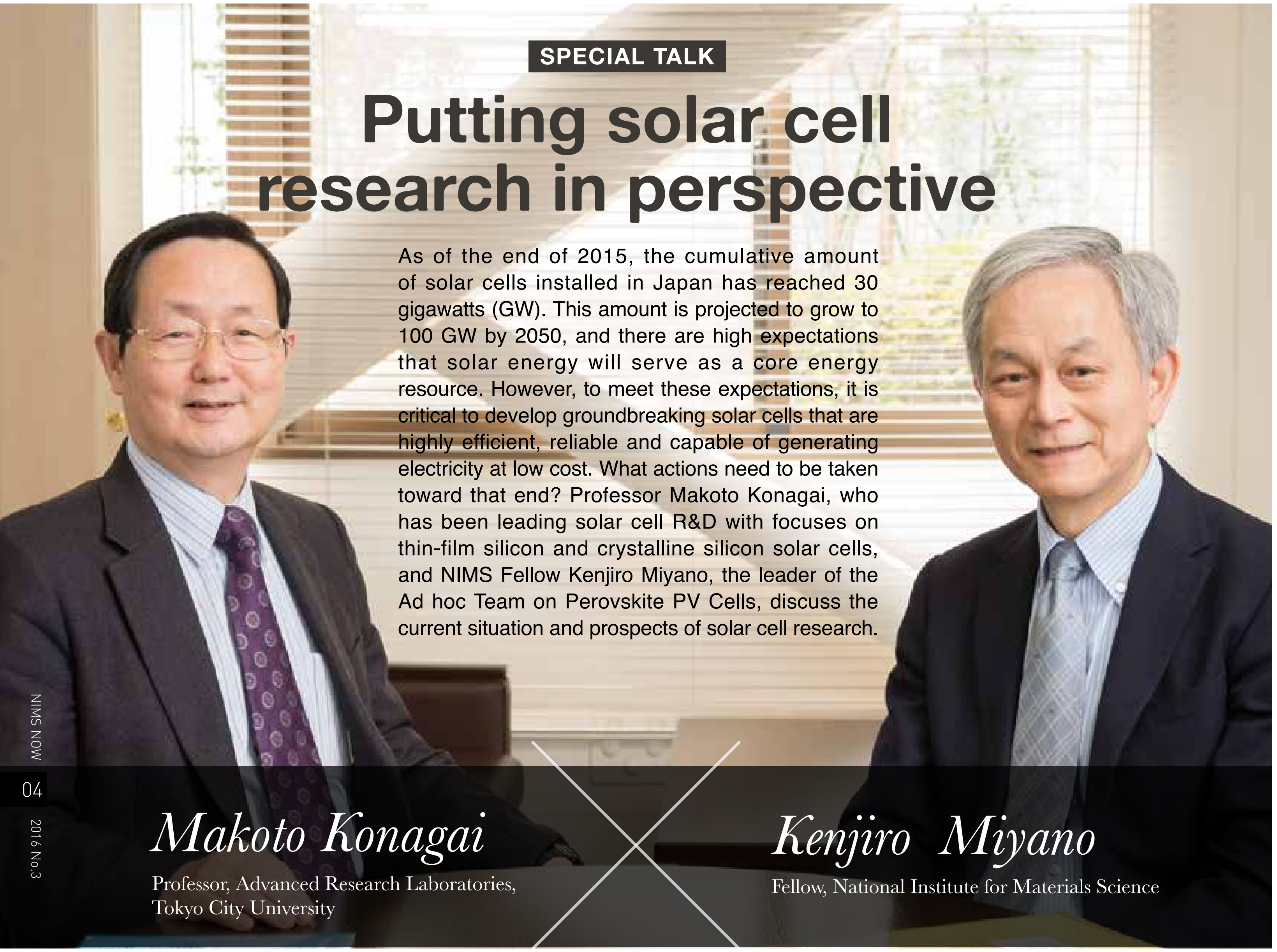
— Unlocking the future with new materials and technologies —

The global energy environment is going through a major change today. Japan, too, is reforming its electric power system in various ways including full liberalization of its electricity retail market. Concurrently, expectations are rising for the utilization of earth-friendly renewable energy sources such as sunlight, wind power, geothermal heat and biomass. In particular, Japan's cumulative photovoltaic (PV) power generation capacity has exceeded 30 gigawatts, the third highest in the world after China and Germany. The global solar electricity market also has been growing steadily, and solar electricity now accounts for about 1.3% of global electricity demand.

On the other hand, PV power generation still has many issues to overcome including higher cost and lower efficiency compared to such conventional means as thermal and nuclear generation. Amid the situation, NIMS is developing intriguing materials and methods designed to increase the efficiency and decrease the cost of PV power generation. In this issue, we will take a close look at leading-edge research on solar cells by NIMS, which has been developing new materials and making modifications to existing materials toward resolving these issues.







SPECIAL TALK

Putting solar cell research in perspective

As of the end of 2015, the cumulative amount of solar cells installed in Japan has reached 30 gigawatts (GW). This amount is projected to grow to 100 GW by 2050, and there are high expectations that solar energy will serve as a core energy resource. However, to meet these expectations, it is critical to develop groundbreaking solar cells that are highly efficient, reliable and capable of generating electricity at low cost. What actions need to be taken toward that end? Professor Makoto Konagai, who has been leading solar cell R&D with focuses on thin-film silicon and crystalline silicon solar cells, and NIMS Fellow Kenjiro Miyano, the leader of the Ad hoc Team on Perovskite PV Cells, discuss the current situation and prospects of solar cell research.

Makoto Konagai
Professor, Advanced Research Laboratories, Tokyo City University

Kenjiro Miyano
Fellow, National Institute for Materials Science

Beginning of solar cell research in Japan

Miyano Professor Konagai, I believe you are very familiar with the history of solar cell research in Japan from the early days.
Konagai I started solar cell research in 1972 when I was a first-year master's student at Tokyo Institute of Technology. I have been in this career for nearly 45 years. The first solar cell material I studied was gallium arsenide (GaAs). Since then, I have dealt with many different materials. The "Sunshine Project" began in 1974 as Japan's long-term project for R&D of new energy technologies. Then, the inauguration of the New Energy Development Organization (NEDO, predecessor of New Energy and Industrial Technology Development Organization) took place in 1980, which has been promoting collaboration between the industry and academia in R&D of solar cells.

To make more efficient silicon solar cells

Konagai At present, 40 GW of solar cells are manufactured worldwide annually. Silicon (Si) is the dominant solar cell material, accounting for 90% of all materials used. However, the energy conversion efficiency of crystalline Si has not been improved since it reached around 25%. I think we need to take bold action to achieve conversion efficiency of 28 to 29%, which is considered to be the theoretical maximum.
Miyano At NIMS, we are conducting research on Si from the economic viewpoint. For instance, we developed a new method to grow single crystal Si from a seed crystal. This method greatly reduced production cost compared to the previous method which was originally developed to grow crystals for integrated circuits. The resulting conversion efficiencies are very similar between the two methods.
Konagai I agree that cost reduction is a very important issue. Also, it is extremely difficult to dramatically increase conversion efficiency using Si alone. In this regard, we have high expectations for tandem (multijunction) solar cells, consisting of Si cells stacked with several semiconductors that are capable of absorbing sunlight at various wavelengths that cannot be absorbed by Si cells. Rapidly growing Chinese industries are also interested in tandem solar cells, and according to report on solar cells titled "International Technology Roadmap for Photovoltaic (ITRPV)," the prevalence of tandem solar cells is expected to grow to 10% of all Si solar cells by 2025.

New concepts to create innovative materials

Miyano The latest trend of solar cell R&D is to develop materials that are superior to Si in terms of cost and conversion efficiency.

Accordingly, NIMS has been conducting research on III–V compound semiconductors, which are a combination between group III elements in the periodic table such as aluminum (Al), gallium (Ga) and indium (In), and group V elements such as arsenic (As) and nitrogen (N). Because group III and V elements absorb light at different wavelengths, the combination of these two groups enables utilizing sunlight in a wide range of wavelengths and thus increasing power generation efficiency. However, it is difficult to control interfaces between different stacked semiconductors. We are currently developing a technology to solve this issue. This technology is critical to successfully fabricate tandem solar cells.

We are also working to develop quantum dot solar cells. The idea behind this technology is to achieve high conversion efficiency taking advantage of quantum effects by fabricating a nanosize structure called a quantum dot in a crystal.
Konagai It is not appropriate to focus our research efforts exclusively on Si for the reason that Si is the dominant solar cell material. To create highly superior solar cell products, it is important for us to develop new materials by constantly applying several new concepts.

Discovery of perovskite materials

Konagai About three years ago, perovskite-based materials suddenly became known to photovoltaics research field. What we call perovskite is essentially ionic crystals of lead iodide having a crystal structure called perovskite. I was utterly surprised by the fact that these materials marked a conversion efficiency of 12% in initial studies. If I were a little younger, I definitely would work on perovskite. It is a big mystery to me that materials of such high potential remained undiscovered until recently.
Miyano Actually, perovskite materials had been studied in Japan since the 1990s. But they were perceived as light-emitting materials at that time. However, if the materials emit light, the light can be used to generate electricity, but no one thought of that then.

NIMS has been taking two approaches in perovskite research. The first approach is to aim for high conversion efficiencies. In fact, Dr. Liyuan Han's group has achieved a conversion efficiency of more than 18%. The second approach is to focus on basic research in the framework of GREEN – the Global Research Center for Environment and Energy based on Nanomaterials Science (see page 6 for research at GREEN). The secret to high power generation efficiencies of perovskite materials must lie in the characteristics of the materials themselves. In this view, we aim to identify the mechanism, and then establish a roadmap for its application.
Konagai Reliability plays a major role in reducing power generation cost. That is because if solar cell products break down easily, cost will increase over the long run.
Miyano It is generally believed that perovskite materials do not last very long. However, based on a series of basic research conducted at NIMS, we have identified factors related to stability in considerable detail. In subsequent studies, we will try to formulate strategies to achieve long-term stability.

More ideas through interdisciplinary interactions

Konagai My impression of Japanese research institutes is that they are conducting solar cell research in isolation without coordination. I hope NIMS will play a leading role in promoting collaboration.

It is more challenging than those on transistors and LEDs. That is the very reason that solar cell research is so much fun.

Makoto Konagai

A systematic approach is vital to increase conversion efficiency. Fortunately, all necessary characterization technologies are available at NIMS.

Kenjiro Miyano

Miyano Different solar cell materials are studied separately by researchers with different specialties, and almost no interaction takes place between the groups. It is a shame that this is the common practice. In fact, there are cases where groups in certain fields are dealing with some unsolved issues, while groups in other fields already have found a solution to the same issues. Researchers should interact with other scientists with diverse backgrounds across different disciplines. I hope NIMS will provide researchers with opportunities for vigorous interactions.

Also, to increase the conversion efficiency of solar cells, it is necessary to take systematic measures rather than random and unorganized measures. Fortunately, a broad array of characterization technologies is available at NIMS. As such, when we create new sample materials, we can even analyze the distribution of elements in these materials immediately. When we detect sudden high conversion efficiencies, we often find unexpected structural features in the sample materials. By understanding the relationships among parameters of sample fabrication, the resulting conversion efficiencies and the structure of sample materials, it may be possible to purposefully create materials with desirable structures. I want to take full advantage of such strength NIMS offers.

Konagai Solar cells already have been in use by many households, but to make solar energy a core energy resource, more innovative ideas need to be incorporated. I hope that young people will engage in solar cell research with new ideas and dreams.

(by Shino Suzuki, PhotonCreate)

GREEN's effort in basic research on perovskite solar cells

The research contributes to the enhancement of cell performance and the understanding of the mechanism

Perovskite solar cells are drawing much attention as next-generation solar cells due to their high efficiency and low production cost. However, before they can be put to practical use, there are many issues to overcome such as low reproducibility, low stability and low durability. To tackle these issues, GREEN launched the "Ad hoc Team on Perovskite PV Cells" in October 2014. Consisting mainly of researchers with experience in R&D of organic solar cells, the team has been carrying out basic research on perovskite solar cells, taking full advantage of GREEN's specialty in calculation/measurement techniques and materials development technology. Here are some accomplishments made by the team.

A perovskite layer is formed after a solution containing a perovskite material is covered on a substrate. In conventional methods, the solution must be applied onto a titanium oxide layer with a complex porous structure in order to facilitate crystallization. However, those methods are associated with low stability and low reproducibility caused by moisture and oxygen entering into the perovskite layer. The team successfully fabricated perovskite layers with enhanced performance by strictly controlling the surrounding environment, as controlled during the fabrication of organic thin film solar cells, and by eliminating a porous structure in the substrate.

In addition, the team made modifications to the perovskite material application process. It developed a new fabrication method involving the addition of chlorine, which made it possible to form a perovskite layer with even thickness and a smooth surface. With this new method, it is now feasible to fabricate perovskite solar cells with high reproducibility and high stability.

Team members Yasuhiro Shirai and Masatoshi Yanagida enthusiastically say, "Since perovskite layers can be fabricated at a low temperature range of less than 140°C, they are compatible with lightweight and flexible substrates such as plastics. For this reason, the industrial community is very much interested in them. However, further basic research is necessary as the mechanisms of perovskite solar cells generating electricity have not even been understood. We will intensify our research efforts in hope of realizing practical use of the cells as soon as possible."

(by Kumi Yamada)

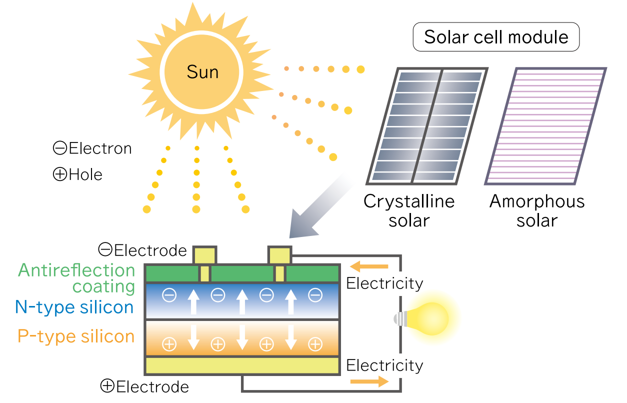
Yasuhiro Shirai (left) and Masatoshi Yanagida (right), members of the Ad hoc Team on Perovskite PV Cells, GREEN.

Basics of Solar cells

PRINCIPLE of solar cells

Photovoltaic power generation is a system for converting solar energy into electrical energy using a semiconductor band gap. **A band gap refers to the energy difference between the valence band and the conduction band in semiconductors**, and its value depends on the kind of semiconductors used.

A solar cell body consists of two kinds of semiconductors—n-type and p-type—that are joined together, and two electrodes attached to the top and bottom of the semiconductors. When a solar panel is exposed to sunlight and absorbs solar energy, pairs of electrons and holes are made at the junction area. Then the electrons move into n-type and the holes move into the p-type conduction band. This movement generates a voltage difference, which is extracted in the form of electricity running through conductors connected to the electrodes.

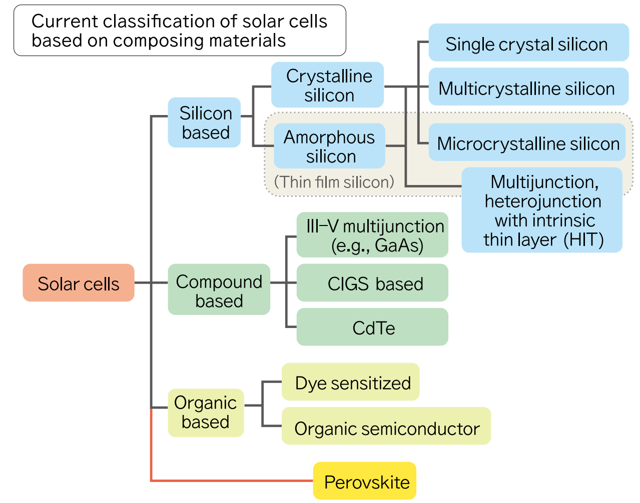


Enlarged cross-section of a solar cell

TYPES of solar cells

The three most common types of solar cells are **silicon solar cells, compound solar cells** and **organic solar cells**. Silicon solar cells can be further divided into "single crystal silicon," "multicrystalline silicon" and "amorphous silicon." Among them, multicrystalline silicon solar cells are most prevalent today.

Despite their high energy conversion efficiencies, compound solar cells only have limited application, mainly to satellites, as they are very expensive. Among organic solar cells, R&D of dye-sensitized solar cells and organic thin-film solar cells had been carried out. However, since organic materials were found to be relatively unstable and nondurable, the focus of some of the R&D are shifting toward perovskite solar cells/materials.



RESEARCH ISSUES on solar cells

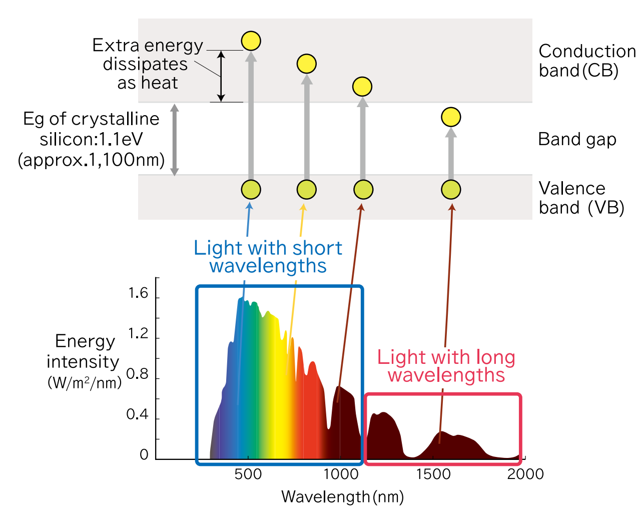
The most critical issue of solar cells is to increase their energy conversion efficiencies.

Sunlight consists of light of various wavelengths, ranging from infrared (IR) with long wavelengths to ultraviolet (UV) with short wavelengths. The energy level of light varies depending on the wavelength, with the rule that the shorter the wavelength is, the higher the energy level is.

However, when IR with long wavelengths enters silicon solar cells, the incoming energy is too low to raise electrons from the valence band to the conduction band. Consequently, the cells are unable to convert IR into electricity. In addition, because only band gap energy can be extracted as electricity, when UV and other light with higher energy levels than the band gap enters the cells, the extra energy dissipates as heat. Consequently, the theoretical conversion efficiency limit for silicon solar cells is estimated to be approximately 30%.

To achieve high conversion efficiencies, active R&D is being conducted on **multijunction (tandem) solar cells**, which consist of a stack of several semiconductors with different band gaps, and **intermediate band (quantum dot) solar cells,** which have an intermediate band within the band gap to facilitate the conversion of light energy into electricity.

Band structure of single-junction crystalline silicon solar cell



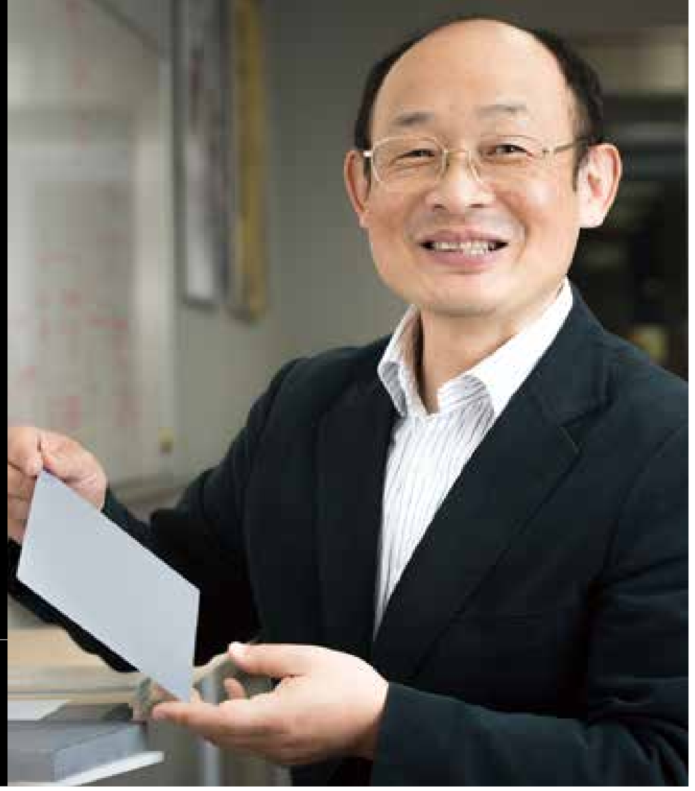
Spectrum of sunlight (total energy of 1kW/m²)

Improvement of Existing Material

New method to create high-quality single-crystal silicon at low cost

Aiming to regain control of the price-competitive solar cell market

In recent years, the solar cell market has been dominated by multicrystalline silicon solar cells that are inexpensive but are of low quality. Amid the situation, an industry-government-academia joint research team led by NIMS's Takashi Sekiguchi developed a method to create high-quality single-crystal silicon solar cells with high energy conversion efficiency at lower cost.



Takashi Sekiguchi

Managing Researcher,
International Center for Materials
Nanoarchitectonics (MANA)

At present, most of commercial solar cells are made by silicon. Due to high-quality requirements, silicon used as semiconductor devices, such as computer CPUs and memory is single-crystal. On the other hand, less expensive multicrystalline silicon is primarily used for solar cells due to priority on low production cost over the quality of end products. However, the energy conversion efficiency of multicrystalline silicon, about 18%, is one-tenth lower than that of single-crystal silicon, which is about 20%. To address these issues, inexpensive ways to create single-crystal silicon were pursued.

One of the pursuers was an industry-government-academia research team consisting of NIMS, including a team leader, Takashi Sekiguchi, who serves as a managing researcher at the International Center for Materials Nanoarchitectonics (MANA); Kyushu University; Japanese manufacturers; Toyota Technological Institute; and Meiji University. The team succeeded in the development of a method for creating single-crystal silicon that consistently yields high conversion efficiencies at lower cost. This achievement was made while implementing the NEDO (New Energy and Industrial Technology Development Organization) project titled "Development of next-generation, high-performance technology for photovoltaic power generation systems" from FY2010 through FY2014.

Modifying the method for creating multicrystalline silicon

Sekiguchi explains the historical background associated with the project. "Japanese industries used to lead the solar cell market before 2006. But other countries eventually gained a lead as low-priced multicrystalline silicon solar cells. The NEDO project was launched under such circumstances in the hope of restoring Japan's competitiveness in this market by developing mono-crystal silicon solar cells with high conversion efficiencies at low cost."

Sekiguchi's research team considered modifying "cast methods" used to produce multicrystalline silicon.

Normally, single-crystal silicon is produced through the following steps: first, melt the high purity silicon feedstock in a crucible at about 1,600°C. After that, hang a small piece of single-crystal silicon (seed crystal) above the crucible and place it in contact with the molten silicon. Then allow the seed crystal to grow and expand. Finally, slowly pull up the growing crystal mass. This crystal growth method is called the Czochralski (CZ) method. It is time-consuming and requires advanced techniques and, therefore, is costly to implement.

On the other hand, multicrystalline silicon is produced by melting silicon in a square mold set in an electric furnace, and allowing the molten silicon to solidify from the bottom. This method was modified to develop a seed cast method that allows crystal seeds to grow into mono crystals (We call them "mono" rather than "single" to distinguish this crystal from CZ). Conventionally, mono crystals are grown in a setting in which the bottom of a crucible is lined with 20 × 20 cm single-crystal silicon plates. Silicon feedstock is melted above the plates and then solidified. This type of seed cast method is called a multi-seed cast method, as multiple crystal seeds are used (Figure 1). This method is easier to perform than the CZ method, as all you need to do is cool and solidify molten silicon. However, the method also has some drawbacks—it is expensive to conduct due to the use of multiple crystal seeds and because crystal defects are created in borders between seed crystals.

In light of these drawbacks, Sekiguchi's research team attempted to develop a new type of seed cast method which employs only one crystal seed. The team set a single-crystal silicon plate holding a lone crystal seed in the center of the mold to grow silicon crystal. This method eliminated the issue of defect formation between adjacent seeds (Figure 2).

Sekiguchi says, "To reduce production cost, we used a creative approach to thermal design and temperature control of the electric furnace. It was especially important to optimize the cooling process of silicon ingot after solidification as a means to prevent crystal defects (dislocations) from generating and multiplying due to thermal stress."

European research institutes also conducted similar studies, but many of them were unable to produce desirable results and ended up their projects immaturely. Sekiguchi's team has built up expertise in crystal defects through many years of experience at NIMS in studying defects in semiconductors. The team took full advantage of its skills, knowledge and know-how for the successful development of solar cells.

"Also, the Kyushu University group played a vital role in designing the internal structure of the electric furnace using its special talent in computer simulation of crystal growth," added Sekiguchi.

Sekiguchi's research team also worked to control contamination during the growth of crystals with impurities, which was a problem associated with seed cast methods.

"In conventional cast methods, the surface of the mold is coated with silicon nitride as release agents to prevent the silicon from sticking. In addition, due to the fact that the heater and insulation materials are made of carbon, and the mold quartz, it is very difficult to prevent the incorporation of these materials into silicon ingots. For this reason, during the growth of silicon ingots, the precipitation of silicon nitride, silicon carbide, or silicon dioxide occurs, degrading the performance of silicon solar cells. We dealt with this issue by minimizing contamination with impurities, and succeeded in the creation of high-quality mono-crystal silicon," says Sekiguchi.

The resulting solar cells achieved conversion efficiencies nearly as high as solar cells made of CZ silicon. Furthermore, Sekiguchi said that an oxygen concentration in the new silicon products was only about 6 ppm as compared to the oxygen concentration of about 20 ppm in CZ silicon.

"At present, we estimate that the production cost using the new method falls under the mid-range between the costs of implementing the CZ and multicrystalline silicon. We believe we can achieve higher conversion efficiencies than that of CZ silicon by further optimizing our method. If this vision comes true, the value of our products will increase even more," says Sekiguchi.

Hope is growing that high-quality and low-priced single-crystal silicon solar cells will become available in the near future and play an active role in slowing global warming.

(by Kumi Yamada)

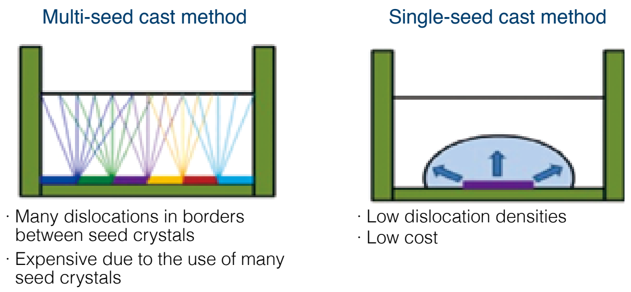


Figure 1 : Conventional multi-seed cast method (left) and the newly developed single-seed cast method (right).

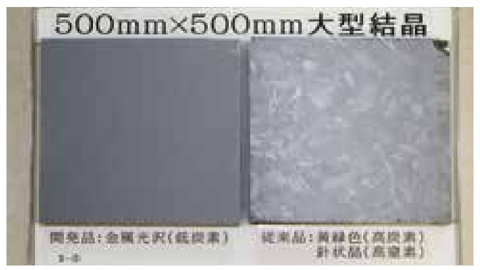
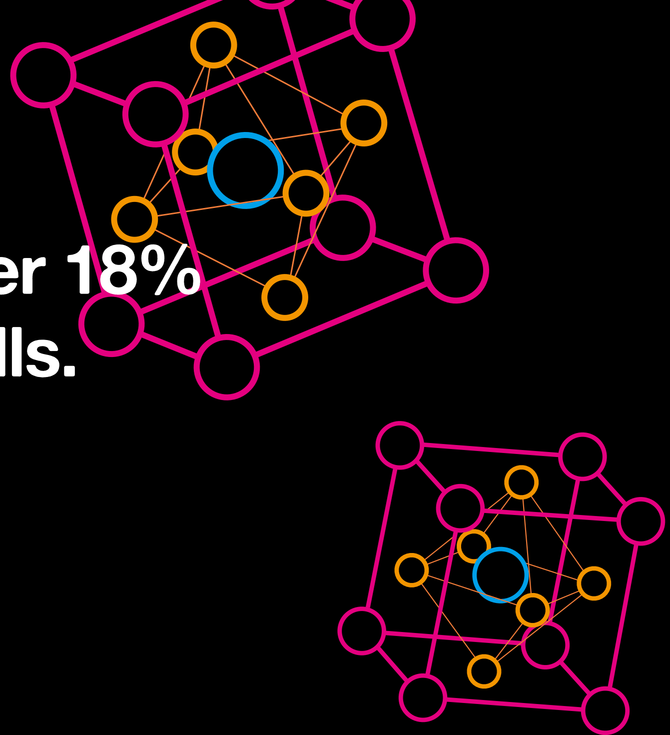


Figure 2 : Mono-crystal silicon created using the single-seed cast method (left). Unlike the conventional product (right), the new product has a metal-like smooth and shiny surface.

Figure 3 : This research project was conducted by staff members from Japanese silicon manufacturers as well as researchers and students from several countries including China, Germany, France, South Korea, and Fiji.

Achieving Conversion Efficiency Over 18% With Large-size Perovskite Solar Cells.



Aiming to realize practical use of "all-inorganic" cells by 2020

Expectations are growing for perovskite solar cells to serve as the next-generation solar cells due to their low production cost and high conversion efficiencies. Competition is intensifying among many countries in the development of these cells toward practical use. Amid the situation, a research group led by NIMS's Liyuan Han is emerging as a groundbreaker in this endeavor.

Han Liyuan

Managing Researcher,
Center for Green Research on
Energy and Environmental Materials

Perovskite solar cells are drawing attention rapidly as their energy conversion efficiencies are nearly as high as those of silicon solar cells, they are made of cheap materials, and they can be produced in large scale at low cost without using high temperatures/pressure and a high vacuum process. On the other hand, they still have many performance issues to be resolved in terms of reproducibility, stability, and durability. Consequently, intense competition is ongoing internationally to achieve practical use of these solar cells.

Liyuan Han of the Photovoltaic Materials Group at the Center for Green Research on Energy and Environmental Materials, NIMS, is among the first researchers to have taken the initiative in the development of perovskite solar cells. The perovskite solar cells developed by Han's research group marked a conversion efficiency of 15% on February 27, 2015. This was the world's first official record verified by an internationally-recognized independent organization for solar cell evaluation. Furthermore, Han's group achieved a conversion efficiency of 18.2% in October, 2015 (Figure 1). This efficiency—comparable with efficiencies of single-crystal/multicrystalline silicon solar cells—has attracted much attention globally.

In most previous reports, conversion efficiencies of perovskite solar cells were made using small cells (0.1 cm^2) without disclosing measurement methods. Such small cells are prone to large measurement errors, and thus the efficiencies measured in this manner are unreliable. In contrast, Han's group successfully created cells of large areas (≥1 cm^2) by making modifications in materials constituting the layer structure of the perovskite solar cells and in fabrication methods. The group also demonstrated the excellent durability of the cells as the deterioration of their performance was only less than 10%, even after 1,000 hours of continuous exposure to sunlight.

Using inorganic materials to overcome the most challenging issue—durability

Perovskite is essentially a mineralogical name for calcium titanate, and compounds having the same perovskite crystal structure are collectively called perovskite-type compounds.

As shown in Figure 2, a perovskite solar cell consists of a glass substrate, a transparent conductive film, a hole extraction layer, a perovskite layer, an electron transport layer, an electron extraction layer, and a back electrode. The cell generates electricity as the perovskite layer absorbs light, which then induces charge (electrons and holes) through photoexcitation. Currently, an organic-inorganic hybrid material with a perovskite structure—a methylammonium lead iodide ($CH_3NH_3PbI_3$) film—is used as a light absorption material. This hybrid material is processed into films by adding the material into a solution and then print. The film product can be mass-production through printing, and the conversion of the substrate from a glass to a film form makes it possible to create flexible solar cells.

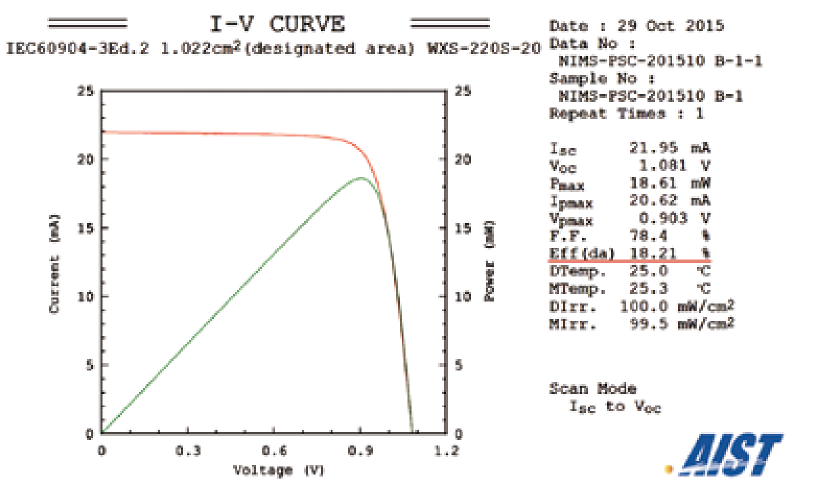


Figure 1: Current-voltage characteristics of perovskite solar cells measured by the Calibration, Standards and Measurement Team at the AIST Research Center for Photovoltaics. The underlined measurement in red represents a conversion efficiency of 18.2% achieved using the newly developed perovskite solar cells.

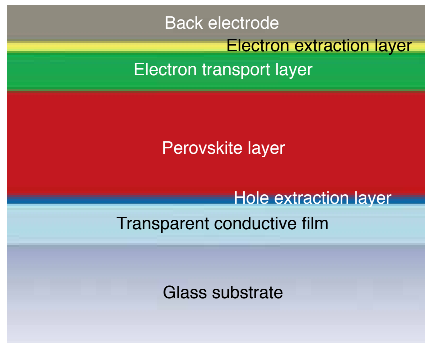


Figure 2 : Structure of a perovskite solar cell.

However, the existing perovskite solar cells have several problems in terms of performance, such as that power generation characteristics vary among cells depending on the conditions under which the films are fabricated, and energy conversion efficiencies fluctuate in relation to the voltage applied to the cells. In addition, these cells also have stability and durability issues as they deteriorate easily when exposed to continuous sunlight.

To deal with these issues, Han focused on the electron and hole extraction layers of the cells. Up to that time, these two layers were made of organic materials. He thought that the stability and durability of these layers would dramatically increase if inorganic materials were used instead of organic ones. He paid particular attention to two kinds of inorganic materials, nickel oxide and titanium oxide, as they are compatible with the energy level of perovskite materials.

On the other hand, to use these inorganic materials as extraction layers, they needed to be transformed into the thinnest possible layers due to their high electrical resistance. Making them into thin layers, however, would also cause an increased occurrence of "pinhole" defects, which reduces the conversion efficiencies of cells. To overcome this dilemma, Han's group reduced pinhole defects by making these inorganic layers thicker. Also, to increase the conductivity of these layers, he added high concentrations of niobium ions to the inorganic electron extraction layers and high concentrations of lithium and magnesium ions to the inorganic hole extraction layers. Experiments demonstrated that the conversion efficiencies and durability of these layers in fact increased as expected. Moreover, the use of thicker inorganic layers with reduced pinhole defects allowed Han's group to expand cell sizes.

Han explains several issues like the process of fabricating the inorganic layers. "At present, organic materials are used for electron transport layers. When we created a thick inorganic layer on top of an organic electron transport layer, we were very careful not to damage the organic layer. Also, when we pasted the inorganic materials, we were fully cautious in completely removing moisture from the working environment, as perovskite layers break down in the presence of water."

In addition, the amounts and ratios of niobium, lithium, and magnesium ions to be added to inorganic films had to be optimized according to the thickness of the films. Han's knowledge and unique know-how developed over years were once again very helpful for his research group to tackle this challenge.

According to Han, the most critical issue to be addressed toward the practical use of perovskite solar cells is to increase their conversion efficiencies and durability. To increase their durability, it is really necessary to replace currently used organic materials with inorganic materials. Accordingly, we aim to create "all-inorganic" perovskite solar cells by additionally replacing organic electron transport layers with inorganic layers. Also, I expect that a conversion efficiency of 20% can be achieved by FY2016 through improvement of perovskite materials. Furthermore, I believe it is possible to achieve a conversion efficiency of even 30% or higher by using perovskite solar cells in tandem with silicon solar cells by placing the former on top of the latter. Whatever approach might be taken, I predict that perovskite solar cells will be in practical use by around 2020."

(by Kumi Yamada)

Solar cells of the future

Ultimate conversion efficiencies by means of “intermediate band concept”

Conversion efficiency of solar cells is determined by the energy required to convert solar energy into electricity (bandgap). NIMS is currently conducting research aiming to convert sunlight at more wide range of wavelengths into electrical energy by forming an “intermediate band” in the bandgap.

Masatomo Sumiya
Chief Researcher,
Wide Bandgap Materials Group,
Electric and Electronic Materials Field,
Research Center for Functional Materials

Sang Liwen
MANA Independent Scientist,
International Center for Materials
Nanoarchitectonics (MANA)

Takeshi Noda
Leader of the Photovoltaic Materials Group,
Center for Green Research on Energy and
Environmental Materials

Utilization of sunlight at all wavelengths may be achieved by III–V nitride semiconductors

The theoretical conversion efficiency limit of ordinary crystalline silicon solar cells is around 30%. To further increase conversion efficiencies beyond this theoretical limit, a creative approach must be taken to find the way to convert sunlight at more wide range of wavelengths into electrical energy. To this end, NIMS is actively engaging in R&D of solar cells using compound semiconductors.

In particular, III–V compound semiconductors consisting of elements in group 13 (group III) and group 15 (group V) of the periodic table, namely gallium arsenide (GaAs) and indium gallium phosphide (InGaP), have bandgap energy close to 1.5 eV (electron volts), which is the optimum energy level for maximum conversion efficiency. Also, as these compounds are resistant to radiation, they already have been put to practical use in space. In addition, III–V compound semiconductors efficiently absorb sunlight, and non-absorbable light efficiently passes through them. Because of these properties, these semiconductors are capable of dramatically increasing conversion efficiencies when they are arranged in a tandem or multijunction structure, comprising a lamination of several types of compound semiconductors with different bandgaps. However, the structure of the tandem structure is so complex that it is difficult to manufacture technologically.

While striving to address this issue, a research group consisting of Masatomo Sumiya of the Wide Bandgap Materials Group and MANA Independent Scientist, Sang Liwen, focused on gallium nitride (GaN) and indium nitride (InN)—two compounds that were widely recognized as the materials for blue light-emitting diodes on the occasion of the Nobel Prize announcements.

A III–V nitride semiconductor, GaN, has a large bandgap (i.e., wide gap, 3.42 eV), and is mixed with InN (0.7 eV) to create InGaN crystal, which enables easier control of the bandgap. If a mini band (i.e., intermediate band) can be formed in the bandgap using wide-gap semiconductor materials, it is feasible to utilize a wide range of sunlight spectrum without using a tandem structure. To achieve this, the research group laminated 30 layers of InGaN thin films with different In compositions over an n-type InGaN semiconductor layer.

The resulting solar cell was able to convert not only a part of sunlight equivalent to intrinsic InGaN bandgap energy but also visible light at longer wavelengths into electricity. This was the first study demonstrating that a III–V nitride semiconductor material is capable of forming an intermediate band. The research group is also trying to laminate III–V nitride semiconductor, that has larger band gap, on top of a GaP-based concentrating solar cell, which has recorded the highest conversion efficiency. It is conceivable to further increase the conversion efficiency by deriving electricity from each cells individually. “By combining this crystal with concentrating solar cells, we hope to achieve the world’s highest conversion efficiency,” says Sumiya.

Solar cells are susceptible to defects formed in cell materials and interfaces. Accordingly, upgrading of solar cell materials, interface control and device fabrication processes leads to an increase in the conversion efficiencies of III–V nitride solar cells. Concurrent with this approach, Sumiya and Sang’s group is also planning to conduct R&D of power conductor devices using III–V nitrides, taking advantage of techniques and know-how they have acquired through solar cell research and development.

Aiming to high efficient solar cells using quantum dots

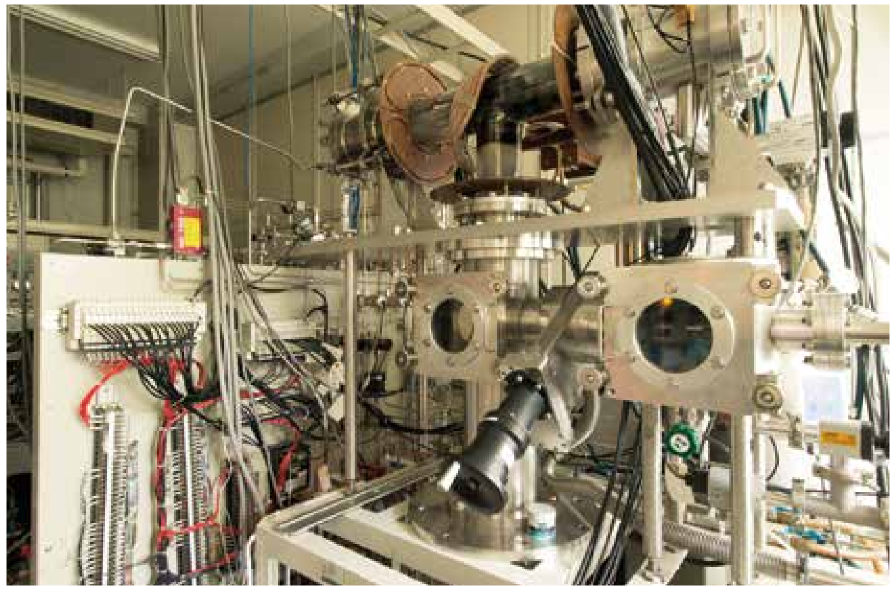
On the other hand, Takeshi Noda of the Photovoltaic Materials Group is working on high efficient solar cells using quantum dots (QDs), where QDs are expected to serve as an intermediate band. We use GaAs and AlGaAs (aluminum gallium arsenide)—other types of III–V compound semiconductors than the abovementioned nitride semiconductors. QD is nanometer-scale structure, so that electrons are confined in all three dimensions. For fabrication of QDs, we utilize “droplet epitaxy”, which is an original technique developed in our Institute.

In this method, a Ga flux is supplied on an AlGaAs surface without an As flux, resulting in the formation of Ga droplets of approximately 10 nanometers in diameter. Then, an As flux is irradiated onto these Ga droplets, which causes reactions between Ga and As, leading to the formation of GaAs quantum dots. Lattice-matched QDs have advantageous for staking of a large number of QD layers with close proximity. “Since solar cells that are designed under the concept of intermediate bands have relatively simple structures, we think they can be manufactured at low cost.” says Noda.

Noda is also working on quantum well (QW) solar cells, in which coupled QWs are used to explore the influences of coupling of electronic states or a mini-band on solar cell properties. Quantum wells are structures capable of confining electrons in one dimension, and they can easily be fabricated using the methods for growing ultrathin-films such as molecular beam epitaxy.

“If solar cells that meet the concept of intermediate bands are successfully created, a conversion efficiency of 60% is achievable in theory. At this moment, there are still many issues to address such as a decrease in open-circuit voltage. We would like to overcome these issues by reviewing current solar cell structures and developing new materials,” says Noda.

(by Kumi Yamada)

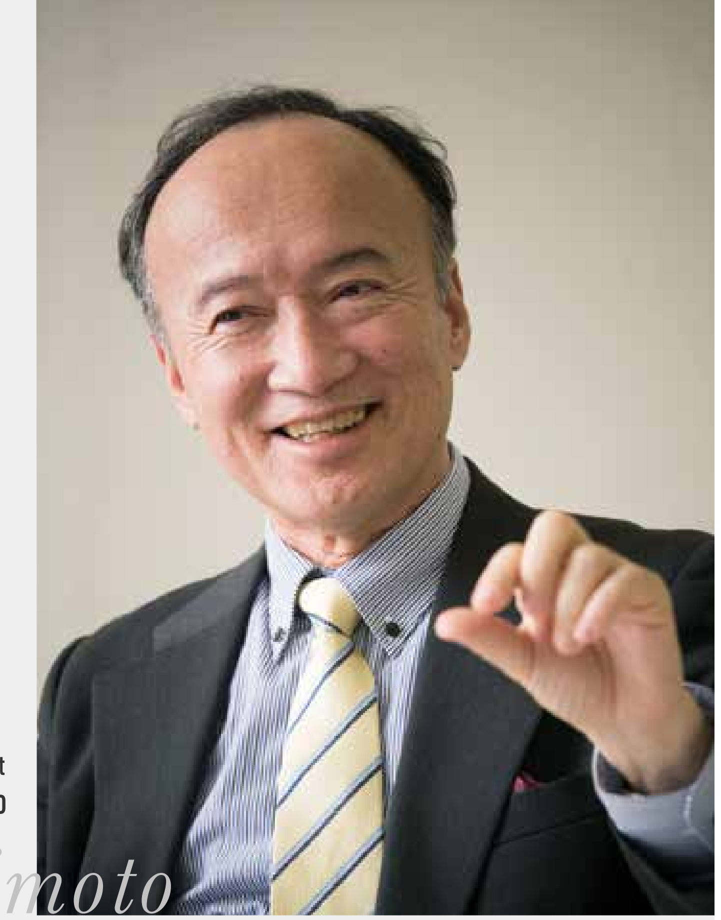


III-V nitride semiconductor thin film growing device

NIMS should serve as materials research hub for the development of innovative solar cell materials

Photovoltaic Power Generation Technology Research Association (PVTEC) promotes the advancement of photovoltaic industries in Japan. As of November 2015, 51 organizations, mostly industries, are serving as PVTEC members. We asked Dr. Hiroshi Morimoto, PVTEC President, about his view as an industrial representative on the current status of solar cell development in Japan and his expectations for NIMS.

PVTEC President
Dr. Hiroshi Morimoto



HIROSHI Morimoto

High expectations for perovskite and III–V compounds

—Would you tell us about the current status of solar cell development by Japanese industries?

Dr. Morimoto With regard to the development of silicon solar cells, there are two major objectives from the industrial perspective: first, to develop low-cost devices with high conversion efficiencies, and second, to develop technologies enabling the integration of photovoltaic power generation systems into the existing electric power system. As for increasing conversion efficiency, national projects are underway targeting a module efficiency of 20% or higher. From the aspect of reducing production costs, a goal has been set to develop devices with costs less than the running costs of a conventional thermal power plant: 7 yen/kWh.

Concerning the issue of integrating photovoltaic power generation systems into the existing electric power system, efforts to develop technologies have been intensifying in relation to the upcoming retail electricity deregulation. Also, the adoption of the Paris Agreement at the Paris climate conference (COP21) in December 2015 is expected to promote the use of renewable energies worldwide. In harmony with these trends, we need to consider how to incorporate solar cell technology into Japan's social system, taking account of increasing public interest in the concept of a "Smart City."

—What is your vision on the development of new materials?

Dr. Morimoto Compound semiconductors, including perovskite and III–V compounds, are promising, new, alternative materials to silicon. In particular, perovskite is drawing much attention given that its conversion efficiency has dramatically increased over the past few years. On the other hand, solar cells consisting of III–V compounds also demonstrate high conversion efficiencies, but are expensive to manufacture. For this reason, their applications have been limited only to certain areas such as outer space. Once these two types of materials have achieved higher conversion efficiencies and lower production costs than conventional solar cells, I believe that the demand will rise rapidly.

—Chinese industries are ahead of Japanese industries in terms of solar cell market share.

Dr. Morimoto The reasons for China's recent dominance over Japan in the solar cell market are due to the fact that German industries developed the systems capable of easily producing inexpensive and higher-performance silicon solar cells, and that China has acquired the systems. For Japanese industries to counter this situation, we need to develop new materials and also systems capable of manufacturing inexpensive and highest-performance devices using the new materials.

—What are your expectations of NIMS regarding these efforts?

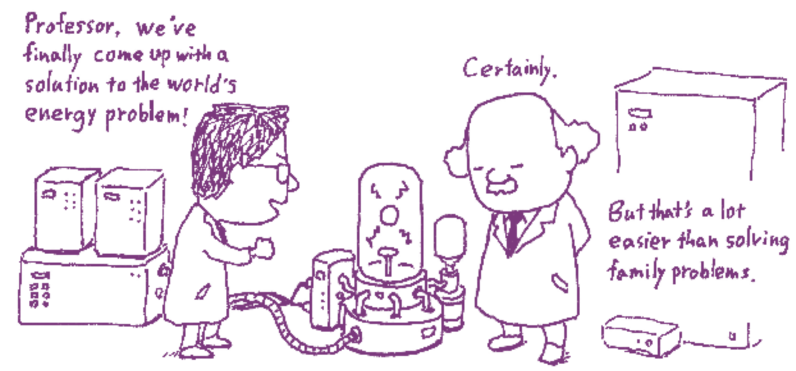
Dr. Morimoto The global community has strong interests in developing low-cost solar cells with high conversion efficiencies. Given that materials development tends to be an extremely long-term endeavor, it would be too much burden for industries to carry out this task by themselves. So, I really hope that NIMS will take the lead in the development of innovative materials. Moreover, I want NIMS to firmly promote collaboration among industries, governments and academia by serving as Japan's materials research hub.

(by Kumi Yamada)

Science is even more amazing than you think (maybe…) 12

Will all energy problems be solved some day?

Written by Akio Etori
Title lettering and illustration by
Shinsuke Yoshitake



In this day and age of mass energy consumption, meeting ever increasing energy demand is a tough issue around the world. International community leaders and experts often discuss and share ideas to resolve this issue. However, concrete solutions have not yet been established.

Currently available energy resources include fossil fuels—such as petroleum, coal and natural gas; natural energy—such as sunlight, solar heat, wind power, hydropower and geothermal heat; nuclear power and biomass. Each type of energy has its own advantages and disadvantages.

Fossil energy is a small in cost and easily accessible resource, but its availability is limited and its utilization results in emission of a large amount of CO_2 into the environment. In contrast, natural energy is an unlimited and environment-friendly resource, but it is difficult to utilize efficiently and economically based on current technology. Nuclear power is an excellent means to generate electricity as it can be acquired in large amount at low cost, and it can be used to generate electricity without emitting CO_2. However, utilization of nuclear power in places like Japan requires meticulous risk management in light of the consequences of the Great East Japan Earthquake.

Biomass and geothermal heat have limited availability at a time, so they also are unsatisfactory as major energy sources.

How can humankind solve energy issues while overcoming the urgent challenges of global warming and air pollution?

The answer to the question might lie in the latest information technology.

For example, while the performance of lithium ion batteries has dramatically improved over years, the batteries are still expensive, large and heavy. Also, they are susceptible to deterioration and take a long time to fully charge. If lithium ion batteries can be replaced with "conductive polymer batteries," which are much lighter and smaller, it may be feasible to make the 75 million automobiles existing in Japan play a role of "mobile, high capacity storage batteries." However, because conductive polymer batteries have a three-dimensional network structure, it is much more complex to analyze their material structure than that of current secondary batteries. For this reason, super-fast computing capability is necessary for the development of conductive polymer batteries. Similar computing resources are also essential for the development of quantum dot solar cells, promising next-generation solar cells with a potential conversion efficiency of 40% or greater.

Furthermore, the same goes for algae capable of producing heavy fuel oil using CO_2 and water. To efficiently produce heavy-oil-producing algae that work in a real world situation, ideas have been brought up to create artificial algae using such information technology as genetic analysis/engineering. In addition, the availability of arithmetic processing technology capable of performing huge amounts of calculations instantaneously is also critical to achieve practical use of thermonuclear fusion which is believed to be very difficult.

Rapid advancement of information technology can make all of these things possible.

When I visited the nuclear plant in Kashiwazaki City, I met Nobel Prize winner Prof. Susumu Tonegawa. He said that if humankind happens to perish, energy issues would be the most probable cause (I agreed with him at that time). But after all, that fear appears to be unnecessary.

Akio Etori: Born in 1934. Science journalist. After graduating from College of Arts and Sciences, the University of Tokyo, he produced mainly science programs as a television producer and director at Nihon Educational Television (current TV Asahi) and TV Tokyo, after which he became the editor in chief of the science magazine Nikkei Science. Successively he held posts including director of Nikkei Science Inc., executive director of Mita Press Inc., visiting professor of the Research Center for Advanced Science and Technology, the University of Tokyo, and director of the Japan Science Foundation.

NIMS NEWS

1 G7 Foreign Ministers Visit NIMS during G7 Science and Technology Ministers' Meeting in Tsukuba

On May 16, G7 foreign ministers visited NIMS while they attended the G7 Science and Technology Ministers' Meeting held in Tsukuba, Ibaraki. NIMS President Prof. Hashimoto first provided a briefing on NIMS, along with an international delegation including Aiko Shimajiri, Japanese Minister of State for Science and Technology Policy. Then, the visitors had a tour of the NIMS labs that are developing "atomic switches," key technology for the realization of the human brain computers, and the world's most sensitive, ultra-small olfactory sensors, which may be utilized to detect diseases by examining breath and to identify the sources of food products. Also, the visiting group had an informal meeting with international researchers working at NIMS, at the end of lab tour.

Japanese Minister Ms. Aiko Shimajiri and G7 foreign ministers listening to the outline of NIMS research.

2 3N-Lab as the first LIA in the field of physics in Japan.

Prof. Alain Schuhl (CNRS/INP, Director), Prof. Etienne Gheeraert (NEEL, Co-Director), Dr. Jacques Maleval (Ambassade de France, Conseiller Scientifique), Ms. Cécile Asanuma-Brice (CNRS/DERCI, bureau de Tokyo), Takahiro Fujita (NIMS, Director of administration), Satoshi Koizumi (NIMS,Principal Researcher) and Yoshio Aoki (NIMS, Director of External Collaboration Division) have attended the kickoff meeting

On February 26, Néel Institute, Centre national de la recherche scientifique (CNRS) and NIMS has established the new International Associated Laboratory (LIA) "3N-Lab (NEEL NIMS for Nanosciences Laboratory)" as the first LIA in the field of physics in Japan.

The establishment of this 3N-Lab will strengthen the partnership between these two pillars of nanoscience research institutes, that continues more than twenty years, particularly in the areas of diamond, permanent magnets without rare earth, superconductors and 2D materials.

This collaboration builds on the broader relationship between the GIANT (Grenoble Innovation for Advanced New Technologies) campus and NIMS, especially with the first NIMS "Collaborative Research Center" in Europe located at Néel Institute and MINATEC, and the GIANT office available for Grenoble researchers in NIMS since 2014.

Hello from NIMS

Hi! I'm Martin and I am an ICYS researcher at NIMS. I have been in Tsukuba since my PhD, for which I studied in the Joint Graduate School of Tsukuba University and NIMS. In my research, I am investigating the possibility to overcome present efficiency limitations of solar cells using quantum structures. The combination of excellent facilities and world-class scientists, plus the freedom to pursue my own research ideas in ICYS is really a great combination.

Besides the lab, also in my private life in Japan I took the freedom to experiment a bit – since four years I am living electrically off-grid on a small self-build solar system. Let me tell you, even after six years, Japan just does not get boring. Besides relaxing Onsen, fun Karaoke, or great Traditional Handicrafts, I still keep finding new things to discover about the deep Japanese culture. Last year, we explored the virgin forest of Shirakami-Sanchi, a magical place of untouched nature (yes, even this you can find in crowded Japan).

I am very thankful that Japan has allowed me these discoveries and that NIMS has taken me on this journey to the cutting-edge of material science.

Martin Elborg (Germany)
April 2010 – present
ICYS researcher

NIMS NOW International 2016. Vol.14 No.3
National Institute for Materials Science
http://www.nims.go.jp/eng/publicity/nimsnow/

photo by Michito Ishikawa, Naomi Muto, Takashi Kobayashi
editorial design by lala Salon Associates

To subscribe, contact:
Dr. Yasufumi Nakamichi, Publisher
Public Relations Office, NIMS
1-2-1 Sengen, Tsukuba, Ibaraki, 305-0047 JAPAN
Phone: +81-29-859-2026, Fax: +81-29-859-2017
Email: inquiry@nims.go.jp