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*Full Research* in Society, for Society

# AIST TODAY

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MESSAGE

## AIST Has Returned to Normal Operation!

FEATURE

## Photovoltaic Research at AIST

## Research Hotline

UPDATE FROM THE CUTTING EDGE（July–September 2011）

## In Brief

# AIST Has Returned to Normal Operation!

## 1. Introduction

It has been almost nine months since the Great East Japan Earthquake struck. Although steady recovery from the disaster is underway, there are still many people who have to live in inconvenient evacuation centers and temporary houses, reminding us of how devastating the disaster was. I pray for the earliest possible recovery of the affected areas.

AIST was also seriously affected by the disaster, to the extent that AIST Tsukuba, AIST Tohoku, and AIST Tokyo Waterfront had to interrupt their research activities. However, the competition for global innovation does not allow us to stand still for long. Early this fiscal year, I interviewed all of the research unit directors over a one-month period and found that they are determined to revitalize research. Due to the efforts of the entire AIST to restructure the research system, our R&D activities are getting back on track.

Since the disaster, AIST as a public research institution has expressed its intention even more clearly to fulfill its responsibility to contribute to society and is actively assisting in the restoration and reconstruction activities. If you wish to know more about earthquakes, tsunamis, and radiation, or if you have technical issues that need to be addressed in order to resume production, please visit our website.

## 2. Restructuring of the research system

Faced with the serious damage to AIST Tsukuba and AIST Tohoku, we came to the conclusion that in recovering from the damage, mere restoration to the previous state would require too much time and money. We needed to address the treatment of hazardous materials used in the laboratory buildings, such as asbestos-containing materials. Dealing with the power shortage was another pressing issue. Above all, faced with this unprecedented disaster that had struck Japan, we became increasingly aware that more than ever we had to move research forward "in society and for society," as expressed in the AIST's Charter. With this in mind, we decided to join hands to restructure the research system.

In order to dispose low-priority damaged equipment, enhance collaboration between researchers and increase shared research facilities, use space efficiently and eliminate the "mosaic" state, and root out bad practices accumulated over the years since AIST became an independent administrative institution, we set up a task force and started right away. Naturally, addressing the power shortage was considered to be a top priority. Cooperation from AIST's regional centers that were not affected by the disaster is, of course, taken into account. I called for everyone to reduce the entropy of the research environment and make AIST a leading research institution in terms of the lowest possible electrical energy consumption. There are remaining issues in the restructuring of the research system that will take a long time to solve, such as improving the seismic safety of buildings and, in particular, permanently preventing the laboratory drain system from being damaged and the ground from sinking at AIST Tohoku. Regardless of these issues, I believe that due to the restructuring activities that have been implemented, we have established an environment that allows us to conduct full-scale research.

The cooperation between AIST centers made it possible to transfer part of the biological process research from AIST Tsukuba to AIST Hokkaido, research on the long-term reliability tests of solar cells to AIST Kyushu, and 20 % of the stored standard materials to AIST Kansai. Many activities have also been undertaken on a limited-time basis, including sending researchers from AIST Tohoku to universities that are in partnership with AIST.

At AIST Tsukuba only, the "mosaic" state was eliminated by sharing and integrating laboratory space, and 19,000 $m^2$ of space, representing 10 % of the total space, has been made available. In the areas of research infrastructure and research support facilities, scrubbers, clean rooms and constant temperature/humidity rooms, and animal breeding rooms have been reduced by 50, 36, and 40 %, respectively, by means of sharing, integrating, and making appropriate cuts.

Initially, a budget was allocated to the restructuring of the

research system, making the research budget tight. We cut spending through various efforts and were able to increase the research budget slightly.

These efforts have made it possible to reduce electricity consumption by 4,800 kW on a permanent basis. This is a 13 % reduction from the figure for last year. We reduced our electricity consumption in TEPCO's service area by more than 15 %, the target set by the government, by additional efforts specifically for the summer: electricity-intensive research equipment, such as for the calibration of large flow meters, was not used during the summer months; the sites at AIST Tsukuba were shut down in turn; the use of air conditioning systems was reviewed; the use of OA equipment was reduced; the number of fluorescent lights was reduced; and some of the elevators were not used. AIST regional centers in other areas also set high goals for reducing electricity consumption and have made efforts to achieve them. Such efforts saved several tens of millions of yen on our monthly electricity bills. These savings allowed us to increase the research budget and improve the research environment.

This is the result of the close collaboration among the General Affairs Headquarters, Planning Headquarters, Research Environment and Safety Headquarters, research units, superintendents, and facility management service providers. I would like to take this opportunity to express my gratitude to the industries and companies involved for their understanding and cooperation in reducing electricity consumption in the areas of calibration and other many research activities.

## 3. A leap forward

It is undeniable that research activities were interrupted during the restructuring of the research system. To improve the situation as much as possible, we decided to send an additional 30 researchers overseas, particularly young researchers. Although they will stay overseas only for several months, I would like them to take advantage of this chance to work internationally. The restructuring of the research system has provided the opportunity to develop collaboration within our organization. Since I became the president of AIST, I have felt the high level of motivation within our organization to pursue interdisciplinary research. I believe that collaboration with researchers in different fields has increased the potential for the creation of innovative technologies.

There are increasing global expectations for renewable energy, particularly after the nuclear accident. AIST has been focusing its attention on *Full Research* on renewable resources and energy. This research is a large 21st century-type project involving all areas of research at AIST. We will improve our issue-resolving capabilities by achieving results through collaboration and interdisciplinary research.

We will actively work to enhance our functions as an open innovation hub. Since the earthquake disaster, we have concluded agreements with Yokohama City University and Osaka University on comprehensive research collaboration. We expect these collaborations to accelerate research in areas such as life science and nanotechnology. We have also entered an agreement with the Institute of National Colleges of Technology (KOSEN). KOSEN is a large institution of higher education comprising 51 schools (55 campuses) throughout Japan, with a total enrollment of about 50,000 and a total faculty of about 6,000. It is well known that KOSEN is highly rated by industry. It is drawing attention from overseas as an institution producing human resources that support Japan's position as a leading technology nation. AIST will contribute to enhancement of the global competitiveness of Japanese industry through regional collaboration with KOSEN, utilizing its footholds across the country.

As a matter of course, the circle of open innovation is expanding to involve industry and overseas national research institutions. Despite the disaster, collaborative research with the private sector is likely to be at almost the same level as in the previous year. As of the end of September, AIST is a member of 16 technology research associations. Many of the associations wish to have research facilities at AIST. The restructuring of the research system has made it possible to provide space for them. We currently have 31 research collaboration agreements with overseas research institutions. As reported by the media, the agreement signed this spring with the Agency for the Assessment and Application of Technology (BPPT) of Indonesia includes support by BPPT and AIST for research being conducted by a Japanese tire manufacturer to improve the productivity of natural rubber in Indonesia using AIST's botanical engineering. We will focus more on activities to support the global strategies of the Japanese private sector in terms of research.

**Tamotsu NOMAKUCHI**
President,
National Institute of Advanced Industrial
Science and Technology


# Overview and Vision of Photovoltaic Technology and Description of the Research Center for Photovoltaic Technologies

## Circumstances surrounding solar power generation

Global solar cell production has been growing since the 1990s and exceeded 1 GW in 2004, when the former Research Center for Photovoltaics was established. Since then, production has increased consistently at an average annual rate of more than 30 % and exceeded 20 GW in 2010. This is probably the result of the global movement toward non-fossil fuels and low-carbon energy sources. In 2004, Japan accounted for 50 % of global solar cell production but has been displaced by China and Taiwan as the world's top producers. The current Japanese share of solar cell production is below 10 %. The issue in developing solar cell manufacturing as a domestic industry is how to address the trend of decreasing prices and compete with emerging solar cell producing countries.

## Toward the establishment of a new research center

Under these circumstances, AIST must act as a leader in future technology development, a neutral coordinator and referee, and a key player in solving common issues.

The sustainable development of technologies requires the establishment of a self-contained technological system as well as an academic system. Solar power engineering encompasses various fields including semiconductor engineering, electrical engineering, and chemical engineering, and can hardly be said to have its own established technological system. Solar cells need to be considered at the device, module, and system levels. New concepts, knowledge, and technologies inherent in a complex system are involved in solar cell research. Therefore, the research needs to be expanded to include new areas that cannot be addressed by traditional academic disciplines and technologies. The new Research Center for Photovoltaic Technologies has been established according to this background and understanding.

## Organization of the Research Center

The organizational structure has changed from a vertical structure, where teams were organized according to research areas such as materials and technologies, to a horizontal structure, where teams are organized according to technological characteristics such as the developmental stages and roles of technologies.

The Center consists of three groups. Two groups, the Industrialization Promotion Group and the Industrial Infrastructure Group, have been formed with an understanding of the increasing importance of close collaboration between AIST and industry. The other group, the Innovative Basic Research Group, has been formed to meet the need for continuous and innovative basic research. In addition, the Planning Coordination Section has been established with responsibility for general management, including safety management, and planning coordination with organizations inside and outside AIST.

1. Four teams have been formed within the Industrialization Promotion Group: the Advanced High Efficiency Processing Team, which is working to enhance efficiency; the Advanced Low Cost Processing Team, with a focus on reducing costs; the Innovative Technology Transfer Team, responsible for rapidly transferring technologies at a certain maturity level to industry; and the Collaborative Module-Reliability Research Team (located in AIST Kyushu), responsible for improving the reliability of PV modules in collaboration with the Innovative Technology Transfer Team.

2. Two teams have been formed within the Industrial Infrastructure Group: the Calibration, Standards and Measurement Team, which is in charge of calibrating primary reference cells and evaluating the performance of solar cells from a neutral standpoint; and the PV System and Application Team, responsible for technology development including system-level evaluation and diagnosis.

3. Two teams have also been formed within the Innovative Basic Research Group: the Next Generation Device Team, with the mission of developing devices to achieve both a power generation cost of 7 yen/kWh and a conversion efficiency of more than 40 %; and the Next Generation Material Team, responsible for developing materials for such devices. As a dual responsibility to the Energy Technology Research Institute, this latter team also has the task of promoting collaboration between the two units.

With the increasing pressure on many governments around the world to change their energy policies after the Great East Japan Earthquake of March 11, 2011, expectations for solar power are increasing and it is being evaluated more carefully. Solar energy has long been a "dream energy" for humans. We must take on the challenge of making this dream a reality.

Director,
Research Center for Photovoltaic Technologies
**Michio KONDO**



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# Photovoltaic Devices Characterization Technologies

Sunlight is an enormous energy source. The amount of solar energy that falls on the Earth's surface in one hour is the same as the amount of energy consumed by the world's population in one year. Research, development, and introduction of photovoltaics are moving forward worldwide. Technologies to accurately characterize the performance of solar cells and modules are therefore becoming increasingly important to support their mass introduction, at all stages from the basic research and development to the production, installation and use (Figs.1 and 2).

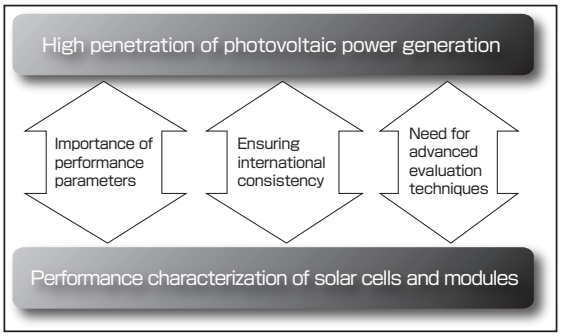



Fig. 1 Importance of photovoltaic devices characterization technologies

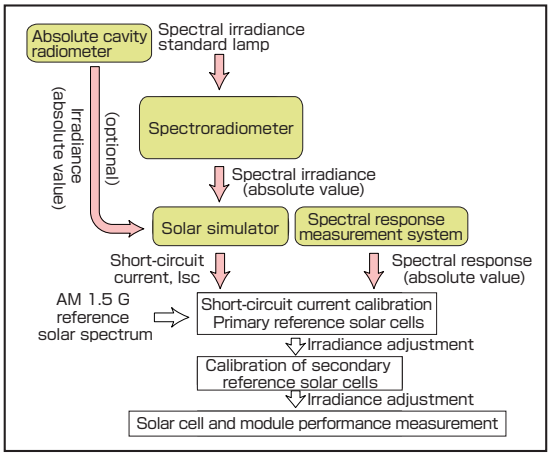



Fig. 2 Flow of calibration of reference solar cells and performance characterization of solar cells and modules

## High-accuracy evaluation technology for new types of solar cells and modules

We are focusing on the development of technologies for high-accuracy characterization of the performance of solar cells under the standard test conditions (STC, i.e. 1 kW/m$^2$ irradiance, AM1.5G spectrum and 25 °C device temperature) generally used to rate the performance of solar cells and modules, as well as the power generation characteristics of solar cells at various temperatures and irradiances that are important when using them. As a neutral organization, we evaluate the performance of new types of solar cells and modules, which are constantly being developed by manufacturers and research institutions, in an internationally consistent manner.

To ensure and further enhance international consistency, we make international comparison measurements of solar modules in collaboration with solar cell evaluation organizations in Europe and Asia (Japan, Korea, Thailand, Taiwan, China, India). Recently, we have developed a technology and related equipment for measurement of the spectral response characteristics of the whole or any part of a commercial-size solar module, which is important for practical application but has been difficult to realize.

## Calibration technology for reference solar cells

We have quantitatively evaluated the uncertainty in the calibration of primary reference solar cells to accurately adjust irradiance, which is of the greatest importance in evaluating solar cells with high accuracy. We acquired ISO/IEC 17025 Testing and Calibration Laboratories Certification based on international mutual recognition of testing and calibration laboratories, and, in September 2009, began to provide calibration services for primary reference solar cells to industry. We have developed the world's first solar simulator for the calibration of secondary reference solar cells, which allows indoor calibration of such solar cells.

We are one of the four World Photovoltaic Scale (WPVS)-qualified laboratories in the world. WPVS is an international comparison scale for primary reference solar cells.

Research Center for Photovoltaic Technologies
**Yoshihiro HISHIKAWA**

# Photovoltaic Power Generation Evaluation Technologies

## Energy-based evaluation of solar cells

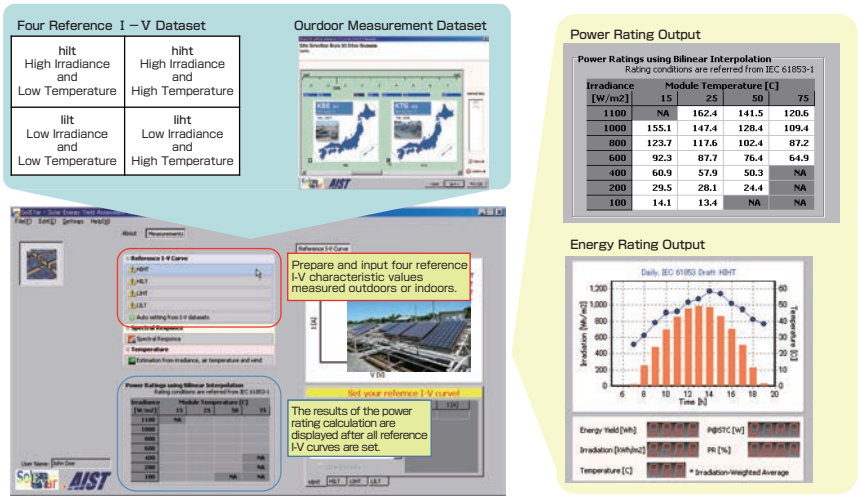
An energy rating is the measurement and evaluation method that can determine which solar cells among various types generate the largest output power (energy) in a certain period.

If we take agriculture as an example, it is important to predict the yields of crops such as fruits. Farmers can maximize profits by choosing crops that are suited to the climate. It is important to identify which crops are appropriate for a particular region; for example, apples in the case of Aomori (cool-temperate climate) and pineapples in the case of Okinawa (subtropical climate).

Similarly, it goes without saying that the profits of a large-scale solar power plant ("mega-solar" power plant) depend on its annual power generation. Selecting the right type of solar cells is therefore increasingly important.

## Description of power generation evaluation technologies

The energy rating is more than merely adding other test modes to standard test conditions for a system's power output rating. To evaluate the total power output during a specific time period, changes in the incident angle characteristics and the solar spectrum due to the changing position of the sun need to be taken into account. It is also necessary to predict how many degrees the temperature of the solar cells will rise and how much this temperature rise will affect the generation of power. The energy rating is a measure to describe the natural behavior of solar cells as accurately as possible. Complex and time-consuming measurement techniques cannot meet the needs of industry.




**The newly developed SolEYar calculation system allows easy verification of IEC 61853 (energy rating) calculations.**

Power generation evaluation technologies are required that are simple and internationally consistent. One such set of technologies is embodied in the IEC 61853 standards, "Photovoltaic (PV) module performance testing and energy rating," being reviewed by the International Electrotechnical Commission (IEC). IEC 61853-1 in the table below has been incorporated into the standards, and IEC 61853-2 will also soon be incorporated. IEC 61853-3 is being reviewed to simplify it. IEC has not yet started reviewing the standard test conditions in IEC 61853-4, but they are likely to have a significant effect when implemented.

| | |
|---|---|
| 61853-1 | Irradiance and temperature performance measurements and power rating |
| 61853-2 | Spectral response, incidence angle, and module operating temperature measurements |
| 61853-3 | Performance testing and energy rating of terrestrial PV modules |
| 61853-4 | Standard days (modes) |

## Provision of power generation evaluation technologies

We have made measurements of different types of solar cells in different weather conditions. We are performing outdoor evaluations of general flat PV modules at AIST Kyushu in Saga Prefecture and high-efficiency concentrator solar cells in Okayama Prefecture and Colorado, U.S.A. Based on our solar power simulation technique developed for PVSystem.net, we have developed a calculation system, SolEYar (Solar Energy Yield Assessment Tool), that makes it possible to implement IEC 61853 simply and more accurately. The system provides guidelines for selecting the most suitable type of solar cell for each of several climate modes. To ensure that IEC 61853 is implemented more effectively, we are conducting research and development involving constant measurements of different types of solar cells and weather conditions both in Japan and abroad and summarizing the analysis results obtained.

Research Planning Office of
Environment and Energy
**Kenji OTANI**



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# Addressing Issues Related to Operating and Maintaining Photovoltaic Systems

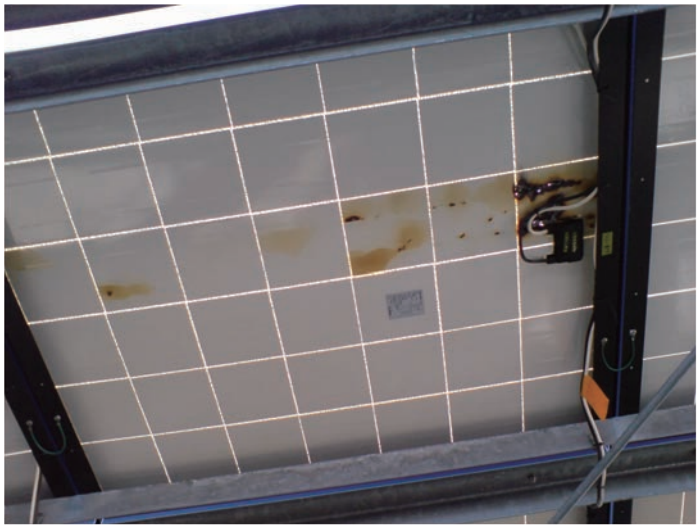
## Maintenance-free myth about photovoltaic systems?

The Great East Japan Earthquake of March 11 shattered the myth that "nuclear power is safe," but the "maintenance-free myth" about photovoltaic (PV) power generation persists.

Solar panels, the main component of a PV system, are installed outdoors and usually cannot be seen up-close by the user. With no movable parts, the system operates silently and starts, operates, and stops completely automatically. Since the output power changes from moment to moment according to the weather conditions and the surrounding environment, the user cannot grasp the performance of the system, making it a rather atypical industrial product. Since sellers and installers of small PV systems, such as residential PV systems, which make up the majority of the installed PV systems in Japan, have no legal obligation to maintain the systems on a regular basis, no operation and maintenance data are available. Someone has to gather such data.

## Examples of PV system problems

AIST Mega-Solar Town commemorated its 7th anniversary in March 2011. Out of a total of 5,645 panels, 116 have been replaced and 79 have had problems (excluding two that were damaged by the earthquake). Nine out of 211 power conditioners had been replaced or repaired in the past, and in 2010, 61 were recalled and replaced. As of March 2011, three were not in operation due to problems.



**Example of a PV panel problem in AIST Mega-Solar Town at AIST Tsukuba**
The burned portion at the right was subjected to high temperature for several months.

Recently, the author conducted a questionnaire survey targeting 483 residential PV systems installed throughout the country to investigate the history of any problems and found that in 72 of them, or about 15 %, one or more panels had been replaced within 10 years after installation. Some of the systems have no history of panel replacement, but an analysis of their power generation records shows the possibility of problems.

In addition, the author and coworkers performed on-site measurements of residential PV systems and found that out of about 30 systems, two-thirds had problems requiring panel replacement.

## Addressing issues of PV system operation and maintenance from the user's perspective

Current maintenance techniques are very undeveloped, and it is difficult for the user of a PV system to check its quality (power generation performance and safety). Regardless of this, PV systems are trouble-free from the user's perspective and will continue to be used as they are for 10, 20, or 30 years unless problems become apparent. This is why appropriate and effective maintenance techniques (hardware) and a social system (software) are required to ensure that PV systems can be used for a long period of time safely and free of concerns. We are working to achieve that goal as soon as possible. While the manufacturer/installer's job ends when the installation is complete, the PV system opration begins from that point onward for the user.

Research Center for Photovoltaic Technologies
**Kazuhiko KATO**

# Reliability of PV Modules

## Introduction

Research and development to simultaneously achieve enhanced conversion efficiency, reduced manufacturing costs, and improved module reliability and lifetime is important in order to reduce the cost of solar power. Module reliability largely depends on module components other than solar cells. It decreases due to deterioration of polymer components such as encapsulants, backsheets, peripheral sealing materials, and potting materials, as well as increased interconnector resistance. Therefore, to improve module reliability, it is important to use new materials with a long life expectancy and evaluate new module structures such as double-glass modules.

## Formation of consortiums and their organizational structures

On October 1, 2009, the Center formed the Consortium Study on Fabrication and Characterization of Solar Cell Modules with Long Life and High Reliability with the participation of 33 companies, the Photovoltaic Power Generation Technology Research Association, and 10 collaborating organizations, and has assessed new module components developed by Consortium member companies using the module fabrication and evaluation line installed at AIST Kyushu, which can handle 1.5 m × 1.5 m commercial size modules (see photo).

On April 1, 2011, we formed the Consortium Study on Fabrication and Characterization of Solar Cell Modules with Long Life and High Reliability , Phase II, with the participation of 64 organizations and 15 cooperating organizations (two of which are participating members). The membership consists of members classified as "A," "B," or "C" and cooperating organizations.


**Main apparatuses of the PV module fabrication and evaluation line**

The responsibilities of "A" members include investigating the mechanisms of module degradation and developing module reliability test methods, developing standards for components that can be used in modules, and making efforts to reflect these standards and the developed reliability test methods in international standards. "B" members are responsible for assessing new module components for effectiveness using the module fabrication and evaluation line. The responsibility of "C" members is to attend technological information exchange meetings to deepen the knowledge of module fabrication and assessment and develop a network of contacts. "C" members are expected to become "B" members in the future. The responsibility of the cooperating organizations is to provide knowledge, materials, and equipment required for module fabrication and assessment as well as module analysis techniques, thereby contributing to the research activities of "A" and "B" members.

## Module assessment technique and test method

Also important is a technique to accurately assess module lifetime. Tests used for certification in accordance with the IEC standards may not produce results that accurately reflect module lifetime. In other words, a module may pass tests in accordance with the IEC standards, regardless of whether its reliability is acceptable.

To represent module degradation in outdoor environments, it is important to develop a test method that combines multiple degradation factors. We not only apply simple temperature-humidity loading and thermal cyclic loading, but also combine light irradiation with these loads. We plan to increase the loads in order to shorten the test time. To do so, we need to ensure that the deterioration mode remains the same as when the module is exposed outdoors and that linearity is maintained. The Consortium is engaged in the research and development of such combined accelerated test methods and highly accelerated test methods. In the development of test methods based on new principles, we are assessing a method in which a PV module is subjected to cycles of application and removal of pressure. Further, in the development of test methods suitable for organic solar cells, we are developing a method for checking for the penetration of moisture of $10^{-6}$ g/m$^2$day, which is likely to affect solar cells. We are conducting these research projects, which are commissioned by the New Energy and Industrial Technology Development Organization, in collaboration with the Photovoltaic Power Generation Technology Research Association.

Research Center for Photovoltaic Technologies
**Atsushi MASUDA**
**Takuya DOI**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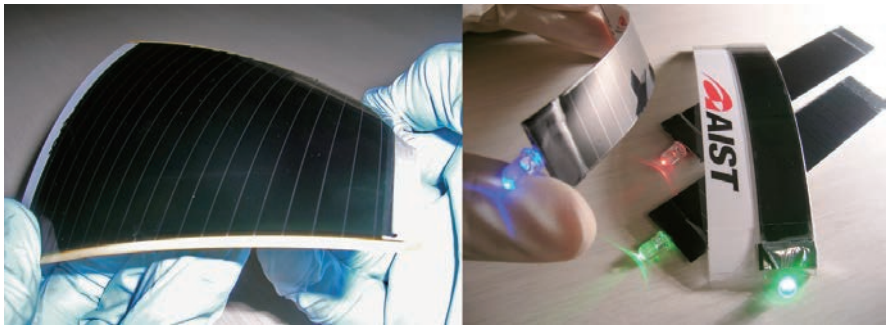
# Development of CIGS Solar Cell Technology (High-Functionality, High-Performance Flexible Submodule)

## Characteristics of CIGS solar cells

CIGS is one of the I-III-$VI_2$ compound semiconductors composed of the I-group element copper (Cu), the III-group elements indium (In) and gallium (Ga), and the VI-group element selenium (Se). Specifically, it is expressed by the formula $Cu(In_{1-x}Ga_x)Se_2$ ($0 \leq x \leq 1$). Solar cells using CIGS as the light-absorbing layer are called CIGS solar cells (including those with part of the VI-group selenium replaced by sulfur (S)). CIGS solar cells are characterized by much higher conversion efficiency than other thin-film solar cells. Conversion efficiency of as high as 20.3 % has been reported for laboratory-level small-area cells.

Glass is generally used as the CIGS solar cell substrate. Light weight, flexible CIGS solar cells can be produced utilizing the characteristics of thin-film solar cells, but they have a lower conversion efficiency than those on a glass substrate. We conducted a study to investigate the cause of this low conversion efficiency and have improved the conversion efficiency of flexible CIGS solar cells.




Outer appearance of the integrated flexible CIGS submodule

## Improvement of conversion efficiency and its significance

First, we developed a method to incorporate sodium (Na) into the CIGS film with high reproducibility and controllability, which is essential for high-efficiency CIGS cells. In this method, a thin sodalime glass layer is inserted between the molybdenum (Mo)-back electrode and the flexible substrate to form a pseudo sodalime glass substrate. This sodalime glass layer is thermally and chemically stable and has the advantage of allowing accurate control of the amount of Na diffused into the CIGS light-absorbing layer. This makes it possible to achieve high performance of small-area flexible cells which is comparable to that of cells on a glass substrate[1].

Second, we fabricated flexible submodules by applying the technology developed for integrated submodules on glass substrates[2]. As a result, we realized an integrated flexible submodule with a conversion efficiency of 15.9 % on a 10 × 10 cm flexible ceramic substrate, which is comparable to that of a glass substrate[3]. This is a dramatic improvement over conversion efficiencies reported by other research institutions, which are about 10 %. We received the 2011 Good Design, Frontier Design Award for the excellent performance and design of our submodule (see figure).

Flexible solar cells have been used only for limited applications, such as mobile power supplies and installation on structures with limited load-bearing capacity and/or curved surfaces where conventional solar cells are difficult to install. If we can develop high-performance flexible modules with a conversion efficiency of more than 15%, we can replace conventional solar cells and develop new applications such as automotive and space applications. Our submodule is a breakthrough that has changed the concept of flexible solar cells.

Research Center for Photovoltaic Technologies
**Shigeru NIKI**
**Shogo ISHIZUKA**

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# Silicon Thin-Film Solar Cells (Development of New Materials and Multijunction Technology)

## Resource-saving and low cost

Silicon thin-film solar cells are only about 1/100 the thickness of crystalline-silicon solar cells, use less silicon, and allow mass production of large, 1 to 2 m-square modules. For these reasons, they are expected to promote the widespread use of solar power. With recent advances in the manufacturing technology for double-junction solar cells consisting of thin layers of two different silicon materials (amorphous silicon and microcrystalline silicon), double-junction solar cells are making inroads into industry worldwide. However, these materials have the disadvantage of absorbing less light due to the thinness of the light-absorbing silicon layer. We have developed a microcrystalline silicon-germanium (SiGe) alloy that can achieve high light-absorption sensitivity with thin films, and are developing high-efficiency multijunction solar cells by combining the alloy with conventional thin-film silicon materials.

## A new material: microcrystalline SiGe

Microcrystalline SiGe can be formed into a thin film on a glass substrate at a low temperature (~200 °C) by plasma-enhanced chemical vapor deposition. The ratio of Si to Ge in microcrystalline SiGe can be freely changed. As the Ge content increases, the infrared absorption increases. Infrared absorption sensitivity exceeding that of microcrystalline Si solar cells with a Si film twice as thick as microcrystalline SiGe film was obtained by adding 10-20 atomic percent (at.%) of Ge to microcrystalline Si (Fig.1). We have achieved a conversion efficiency of 8.2 % with microcrystalline SiGe solar cells and obtained a high output current of about 25 mA/cm$^2$ with a film thickness of 1 μm[1]. We are expecting an output current of about 30 mA/cm$^2$ with 2 μm-thick microcrystalline SiGe solar cells, which is comparable to that of crystalline Si solar cells.

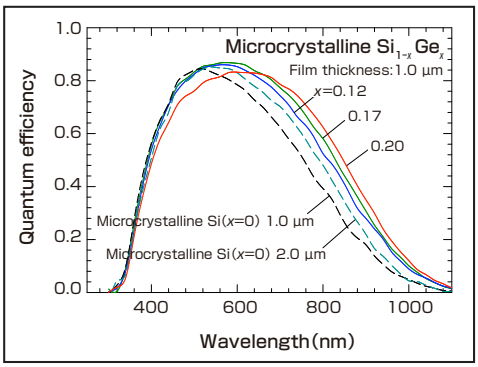


**Fig. 1 Quantum efficiency spectrum of microcrystalline SiGe solar cells with different Ge content (x) (solid lines)**
The microcrystalline SiGe solar cells are half as thick as microcrystalline Si solar cells (dashed lines) but have higher infrared absorption sensitivity.

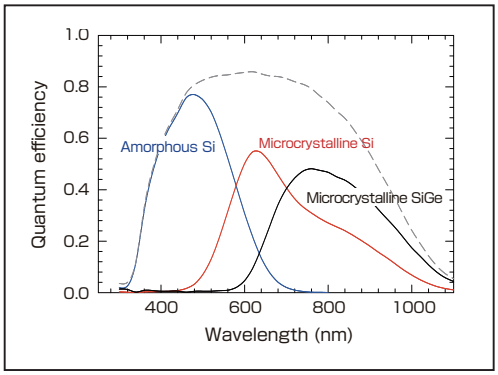


**Fig. 2 Quantum efficiency spectrum of the fabricated triple-junction solar cells**
The solar cells generate power by absorbing the solar spectrum over a wide range through the use of three materials having different wavelength sensitivities (band gaps).

## Development of high-efficiency multijunction solar cells

We have fabricated double-junction solar cells using amorphous Si and microcrystalline SiGe. As a result, the thickness of the solar cell has been reduced to about half that of conventional microcrystalline Si solar cells and an initial conversion efficiency of 11.2 % has been achieved[1]. Currently, we are developing triple-junction solar cells that are expected to achieve higher conversion efficiencies using amorphous Si, microcrystalline Si, and microcrystalline SiGe (Fig.2). We aim to develop such multijunction technology and achieve a conversion efficiency of 15 % by improving the quality of the transparent electrode material used in Si thin-film solar cells and the light-confinement technology.


Research Center for Photovoltaic Technologies
**Takuya MATSUI**



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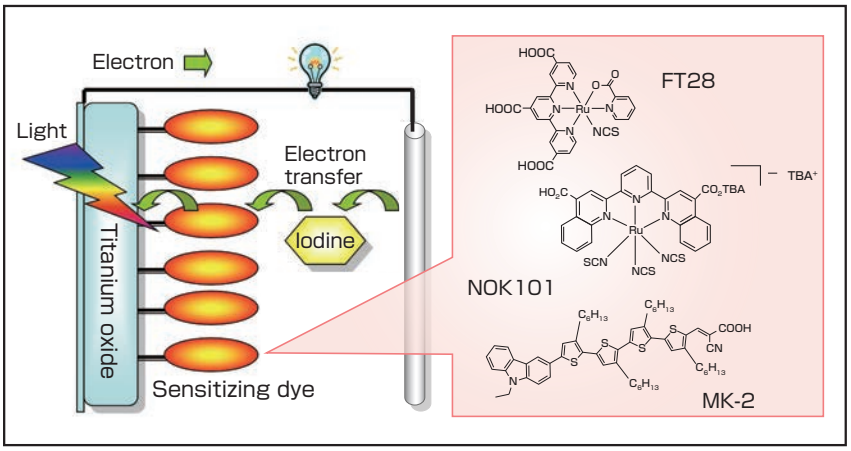
# Dye-Sensitized Solar Cells

## Next-generation solar cells with unique characteristics

A dye-sensitized solar cell is characterized by use of inexpensive semiconductors, such as titanium oxide, and a simple manufacturing by coating that needs no vacuum nor cleanroom facilities. It is one of the next generation solar cells that are expected to significantly reduce production costs. The dye-sensitized solar cell was developed from photographic sensitizer research and is a unique solar cell that is very different in terms of its operating principle, history, and research area from other solar cells. It can be used for large-scale power generation and offers color and design flexibility. Its color can be easily changed by changing the dye. It can generate electricity with high efficiency even when weak light falls on the surface of the cell at an angle. For these reasons, dye-sensitized solar cells are expected to be used for interior applications in the near future.




**Operating principle of a dye-sensitized solar cell and examples of high-performance sensitizing dyes developed by AIST**
The dye-sensitized solar cell is also called a photosynthesis-mimicking solar cell.

## Development of high-performance sensitizing dyes

To commercialize and improve the efficiency of dye-sensitized solar cells, the performance of sensitizing dyes must be further improved. We are focusing on the development of new dyes. Our research on new ruthenium complex dyes that can efficiently utilize near-infrared light at 800 nm and longer wavelengths as well as visible light has shown that FT28 dye (see figure) exhibits performance comparable to that of the world's most efficient complex dye, called black dye. Another ruthenium complex dye, NOK101, has been found to exhibit the world's highest quantum yield in the near-infrared region at 900 nm and longer wavelengths. Since structural modification of the ligand, which is difficult in the case of the black dye, can be easily achieved, the performance of these new dyes would be further improved. The development of metal-free organic dyes is very important in reducing the cost of sensitizing dyes and saving resources. The molecular structure of an organic dye (MK dye)[1] developed by AIST prevents iodine from accessing to the electrode and thereby hinders recombination of electrons. As a result, the dye maintains relatively high photoelectric conversion efficiency without reducing the open-circuit voltage. For the first time in the world, we have added functionality to the molecular structure of sensitizing dye. AIST is therefore leading the way in developing functional organic dyes by changing the molecular structure. This organic dye can now be obtained commercially and is readily available to researchers.

## Toward commercialization

We are not only developing sensitizing dyes but also conducting frontline research on all elemental technologies such as oxide semiconductors, electrolytes, conductive substrates, and stabilization technologies. For example, a solar cell with a new structure[2], which does not use conductive glass, is ideal for mobile power applications. We will contribute to the early commercialization of dye-sensitized solar cells while also focusing on basic research, including the application of computational science to this field and elucidation of the mechanisms involved in the dye-sensitized solar cell.

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References
[1] PCT/JP2007/056383
[2] JP 2010-21091 A

# Development of Organic Thin-Film Solar Cells

## Expectations for use as next-generation, low-cost solar cells

Organic thin-film solar cells are advantageous in that they can be easily installed due to their light weight and flexibility and easily manufactured by printing and coating techniques, and also due to the fact that organic materials are inexpensive and abundant in terms of resources. For these reasons, they are expected to be next-generation, low-cost solar cells, and research and development of them is being carried out at an accelerated pace. The conversion efficiency of organic thin-film solar cells was 5 to 6 % in 2009 and today is over 8 %. Companies in Japan and overseas are making intensive efforts to commercialize such solar cells.

Organic thin-film solar cells can be divided into two groups according to the material and process used: polymer-coated solar cells using soluble polymers, and small-molecule-deposition type solar cells using small molecules. In recent years, research has been conducted using soluble small molecules and small molecules that are insolubilized by thermal conversion. However, polymer-coated solar cells are dominant. An organic thin-film solar cell consists of films of 100 to 300 nm in thickness. Its high efficiency is achieved by bulk heterojunction using mixing and phase separation of the donor, a p-type semiconductor, and the acceptor (usually a fullerene derivative), an n-type semiconductor.

## Roll-to-roll manufacturing by printing and coating techniques

Organic thin-film solar cell materials can be easily turned into ink, and roll-to-roll manufacturing by printing and coating techniques has been attempted. We have fabricated solar cells using simple dip coating and brush coating techniques. A solar cell fabrication process using printing and coating techniques can produce solar cells with low energy consumption as it uses no vacuum process and is the most suitable for roll-to-roll manufacturing. The fabrication process is expected to produce the ultimate low-cost solar cells that we aim to develop. However, many issues remain to be solved, such as atmospheric control and the development of multilayer devices that enable high efficiency. There are also issues related to peripheral components, such as flexible substrates to be coated with organic thin-film solar cells and barrier materials required to increase the durability of the cell. We are investigating the degradation mechanism of organic thin-film solar cells to increase their durability.

**Various types of organic thin-film solar cell submodules providing excellent design flexibility**
This is produced through collaborative research with Mitsubishi Corporation and Tokki Corporation.

## Organic thin-film solar cells making inroads into society

Solar panels are being installed on the roofs of homes and large buildings, as well as at mega-solar power plants. Organic thin-film solar cells are expected to be used in a wide variety of applications, taking advantage of their characteristics such as their light weight, flexibility, and ease of installation, including installation on exterior walls, windows, interior furnishings, vinyl greenhouses, and as emergency power supplies in the event of disaster. We believe that organic thin-film solar cells, with their color and design flexibility, are suitable for people's living conditions and will become disseminated throughout society. Our goal is to promote the widespread use of solar cells through research and development of organic thin-film solar cells, thereby contributing to the realization of a renewable energy society.

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For inquiries about this article : Research Center for Photovoltaic Technologies http://unit.aist.go.jp/rcpvt/cie/index.html

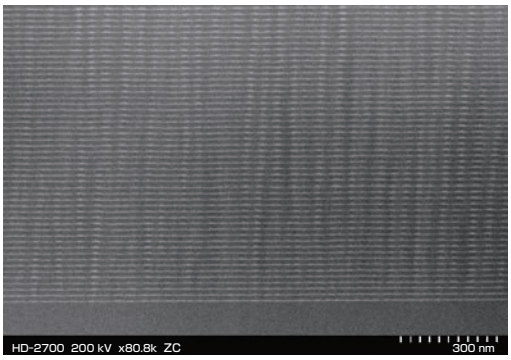

# Development of Innovative Solar Cells

## Introduction

AIST is engaged in the research and development of solar cells from a long-term perspective to dramatically improve their performance, and thereby to contribute to the significant reduction of greenhouse gas emissions by 2050. A dramatic improvement in the efficiency of solar cells will lead to more generated power with less surface area. This is important for Japan with its limited land area, and is an issue directly related to the contribution of solar power to the prevention of global warming. We have formed a group with a number of universities, companies, and research institutions for the research and development of innovative solar technologies commissioned by NEDO. We are playing a leading role in the research and development of innovative, very-high-efficiency solar cells. In the project, we are developing new materials with a highly ordered structure including crystals, and improving the efficiency of multijunction solar cells by stacking the developed materials. We are also researching a new and unconventional concept of solar cells.

## Quantum dot solar cells

Quantum dot solar cells are said to have a theoretical efficiency of more than 60 % and are being researched as very-high-efficiency solar cells[1]. A new light-absorbing band, which is called an intermediate band due to the overlapping of the wave functions of quantum dots, is formed by fabricating a structure with regularly arranged nanometer quantum dots to confine electrons three-dimensionally. Due to this band, light in a wider wavelength range can be absorbed, resulting in high efficiency. We fabricated a semiconductor quantum dot structure by molecular beam epitaxy using III-V compound semiconductors such as gallium arsenide (GaAs). We have fabricated the world's first 400-layer, super-multilayer indium gallium arsenide (InGaAs) quantum dot structure employing an $As_2$ molecular beam and a growth interruption method, without using strain balancing technique. We applied multilayer quantum dot structures to solar cells. As the number of layers increased, the short-circuit current increased and this increase was observed for solar cells with up to 150 layers. This was the first time that an increase in short-circuit current was observed with this many layers of multilayer structures. We also fabricated a 20-layer quantum dot superlattice solar cell with electronically coupled quantum dots and observed a tunnel current flowing in this superlattice mini-band[2].




**Cross-sectional TEM image of the fabricated quantum dot structure (with 50 layers stacked)**
We have successfully stacked up to 400 layers of high-quality quantum dot structures with quantum dots arranged in the growth direction.

## Smart stack technology

We are researching smart stack technology for the fabrication of two-terminal solar cells by stacking individually developed solar cells. We need to develop junction technology that provides optical transparency, low electrical resistance, and high physical adhesion strength. We have attempted several different junction techniques, such as a junction via resin containing conductive particles and a junction using intermolecular forces.

In addition, we are engaged in the research and development of innovative solar cells using new materials such as single crystalline organic materials, nano-silicon, and carbon nanotubes.

Research Center for Photovoltaic Technologies
**Koji MATSUBARA**

References
[1] A. Luque *et al.*: *Phys. Rev. Lett.*, 78, 5014 (1997).
[2] T. Sugaya *et al.*: *Appl. Phys. Lett.*, 97, 183104 (2010).

# Research Hotline

# UPDATE FROM THE CUTTING EDGE

**Jul.-Sep. 2011**

**The abstracts of the recent research information appearing in Vol.11 No.7-9 of "AIST TODAY" are introduced here, classified by research area.**
**For inquiry about the full article, please contact the author via e-mail.**

## Environment and Energy

## Is it possible to write an air electrode by a pencil?

### Drawing an air electrode of lithium air battery by a pencil

A novel air electrode can be easily prepared by pencil-drawing on the surface of a solid state electrolyte to fabricate a lithium-air battery. This battery is based on the oxygen reduction catalytic activity of graphene. The battery provides a snapshot for a future lithium-air battery.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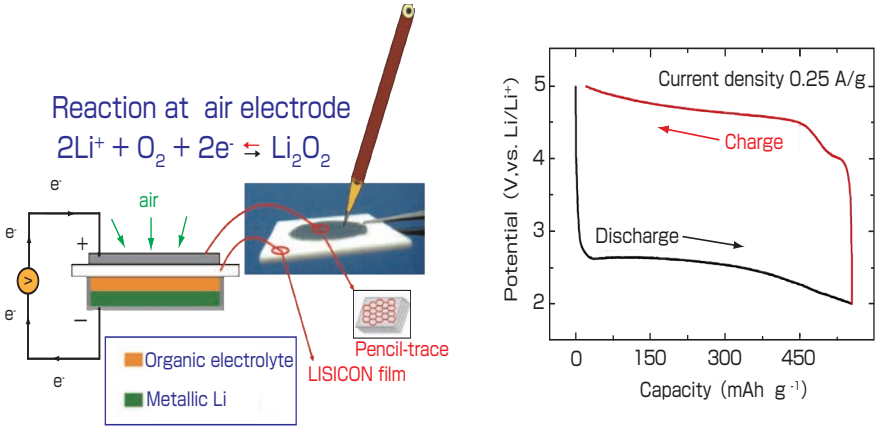


The image of Li-air battery and air electrode drawn by a pencil (left), The charge-discharge curve of the Li-air battery (right)

## Life Science and Biotechnology

## Harmine, a new candidate for sleep disorder treatment

### A circadian modulator which extends the circadian period

We established an assay system using NIH3T3 cells stably expressing a *Bmal1* promoter-driven luciferase reporter gene and used the system to analyze circadian oscillation of the gene. We examined the effects of a *Hoasca* alkaloid, harmine, which has a wide spectrum of pharmacological actions, on circadian rhythms using the validated assay system. Harmine dose-dependently elongated the circadian period. Furthermore, EMSA and Western blot analysis showed that harmine enhanced the transactivating function of RORα, probably by increasing its nuclear translocation. Exogenous expression of RORα also caused a long period, confirming the phenotype indicated by harmine. These results suggest that harmine extends the circadian period by enhancing RORα function and that harmine is a new candidate that contributes to the control of period length in mammalian cells.


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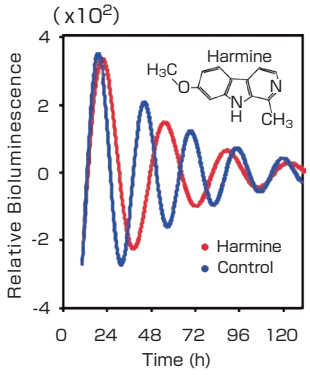
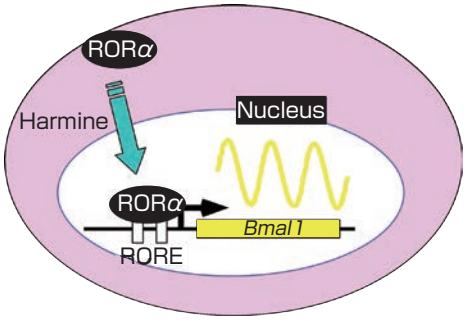



**Measurement of the elongating effect of harmine on circadian period**
Harmine extends period length.




Harmine induces RORα accumulation in nuclei and then the circadian period is extended.

# Development of metal-less bamboo wheelchair

## Metal-less wheelchair with both strength and bamboo feel that can pass through airport security

We have developed a metal-less bamboo wheelchair with a wheelchair manufacturer, Sun-so'ing, based in Oita Prefecture and Japan Airlines International (JAL). Normally, wheelchair users who need to fly must undergo extra procedures such as body search at the airport security, since ordinary wheelchairs contain metal parts. Using the metal-less bamboo wheelchairs, they can remain seated during airport security screening. The JIS fatigue strength test for manually propelled wheelchairs is very strict, and the initial type of plastic parts that supported the wheels easily broke.

To overcome this problem, we have developed a two-point support system in the wheel portion to ensure the durability of the product without using metal parts, and have passed the JIS test. Other innovations such as easy-to-use footrests and brakes are also developed. The metal-less bamboo wheelchairs are already in service for passengers at Haneda, Oita, and Itami airports.

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One-point support system (left) and two-point support system (right) of the frame


JAL rental whealchair counter at Haneda airport



# 0.5 nm ultra-thin gate dielectric film

## Contributes to low power operation of integrated circuits

An ultra-thin gate dielectric film is developed using epitaxially grown crystalline $HfO_2$ in place of amorphous $SiO_2$. Owing to the large dielectric constant of crystalline $HfO_2$ which is 5 times larger than that of amorphous $SiO_2$, an ultra-thin electrical thickness of 0.5 nm is achieved by a 2.5 nm-thick epitaxial $HfO_2$ film. The leakage current is 6 orders lower than $SiO_2$. This technology is applicable to LSI manufacturing without difficulty, because it was developed based on the crystallization mechanism using LSI tools. Ultra-thin dielectric films contribute to the supply voltage reduction and thus the low power operation of integrated circuits.

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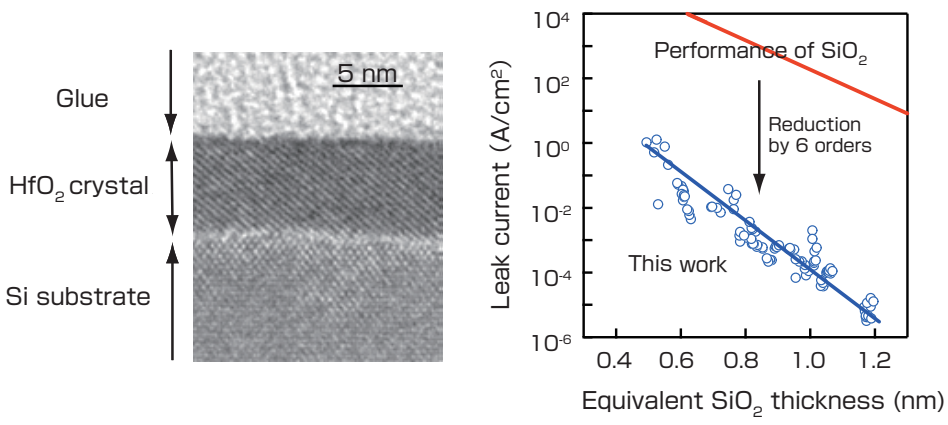


(Left) Transmission electron microscope image of epitaxial $HfO_2$ film on Si substrate
(Right) Advantages of the epitaxial $HfO_2$/Si structure in the scaling of effective oxide thickness and reduction of gate leakage

# Visualization of visitors' comments as an artwork

## A visitor not only appreciates but participates in an exhibition

We have developed a system for visualization of visitors' comments as an artwork for exhibitions. The system allows visitors to not only appreciate but participate in an exhibition. The system includes a system for collaborative knowledge construction. Defining a structure of knowledge for representation of data semantics is usually a costly and time-consuming task. Our system is aimed at construction of knowledge with collective intelligence. Users can add resources and properties as they would with social tagging. The system assists the construction of knowledge using suggestions. In this way, the crews tagged attributions to visitors' comments on site and the system visualizes connections among comments as an artwork. We displayed our system in the 14 th Japan Media Art Festival 2011 and 3,100 visitors' comments were tagged on site and visualized as artworks in the festival.

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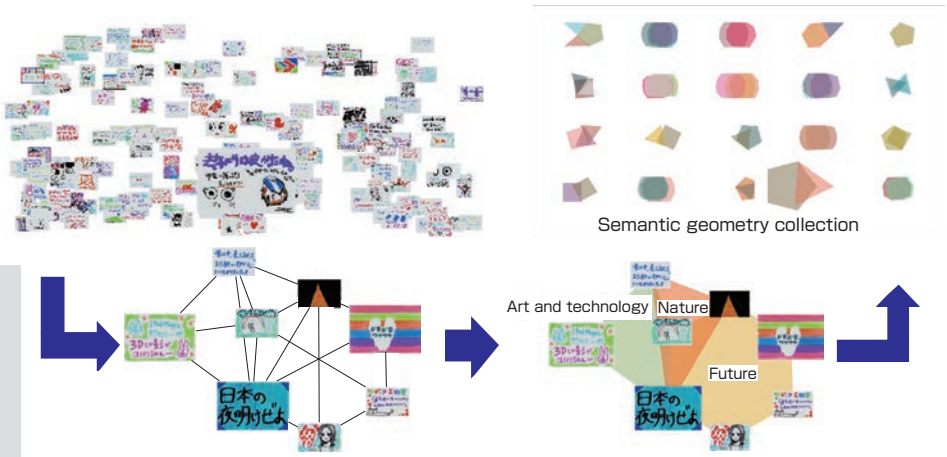


**The process of generating geometical patterns from a set of comment cards**

The system represents connections among visitors' comment cards based on their attributions which are tagged by the collective intelligence. It generates geometrical patterns of a set of the cards as a new artwork.



# An alternative of platinum counter electrodes for dye-sensitized solar cells

## Development of a ternary material with a core-shell structure

AIST has developed a ternary material with a core-shell structure consisting of multi-walled carbon nanotubes, an ionic liquid, and a conducting polymer. It was found that, when used as the counter electrode of dye-sensitized solar cells (DSCs), the material exhibits photoelectric conversion efficiency as high as that of platinum counter electrodes. DSCs are in the development stage and platinum, one of rare metals, is considered to be a promising material of counter electrodes. However, because of the rapidly increasing use of platinum as catalysts in vehicles and fuel cells, there is concern that the supply and demand balance of platinum may be affected. If the new ternary material, which is produced by using simple processes, can replace platinum, then its use would help reduce the consumption of platinum. It would also enable a cost reduction and an increase in the area of DSCs.

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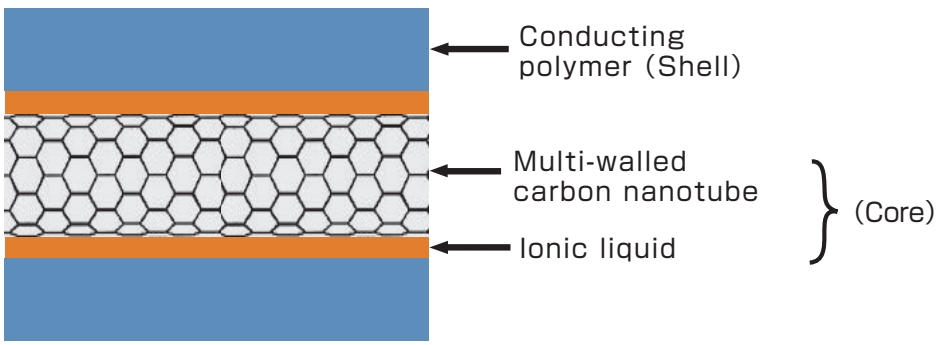
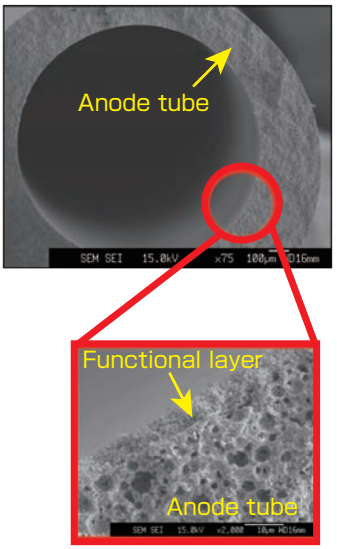



The developed ternary counter electrode material with a core-shell structure

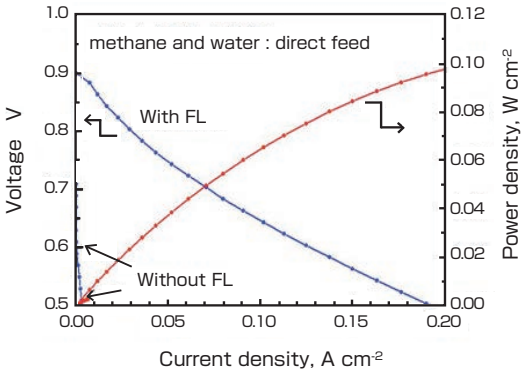
# Low temperature operable micro SOFCs

## First demonstration of power generation by methane direct reformation at low temperature

We report a new concept of an SOFC utilizing a functional layer on the surface of an anode, for the direct reformation of a hydrocarbon fuel using a micro-tubular design. Preparation of the functional layer is cost-effective and the cell with a pure-ceria ($CeO_2$) functional layer was successfully fabricated. The cell displays practical cell performance below 500 °C using methane-water mixture as the fuel gas, and shows enhanced performance compared to one without a functional layer.




Cross-sectional SEM image of the micro tubular SOFC with the functional layer




Performance of the micro tubular SOFC with and without the functional layer (FL) at 450 °C using methane–water fuel

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# Technology for color imaging in darkness

## Successful imaging of color animation of objects in darkness

We have developed a new technique for color imaging of objects in darkness by irradiating infrared light to the objects and by imaging the reflected infrared light from the objects. Along with the surge of recent security consciousness, demand for security cameras such as crime prevention cameras or surveillance cameras rises more and more. However, conventional infrared imaging techniques provide only monochromatic images and have problems in low visibility. Therefore, a higher-performance imaging technique with high visibility is expected. The present technique is based on a highly sensitive infrared imaging technique and a high speed image processing technique. It makes possible to indicate objects in darkness in real time with equivalent or similar color to the color of the objects under visible light, resulting in a promising technique for various applications such as for security cameras, assist cameras for vehicles, etc.


Example of normal color image under fluorescent lamp light (left) and example of color image in darkness taken by the developed system (right)

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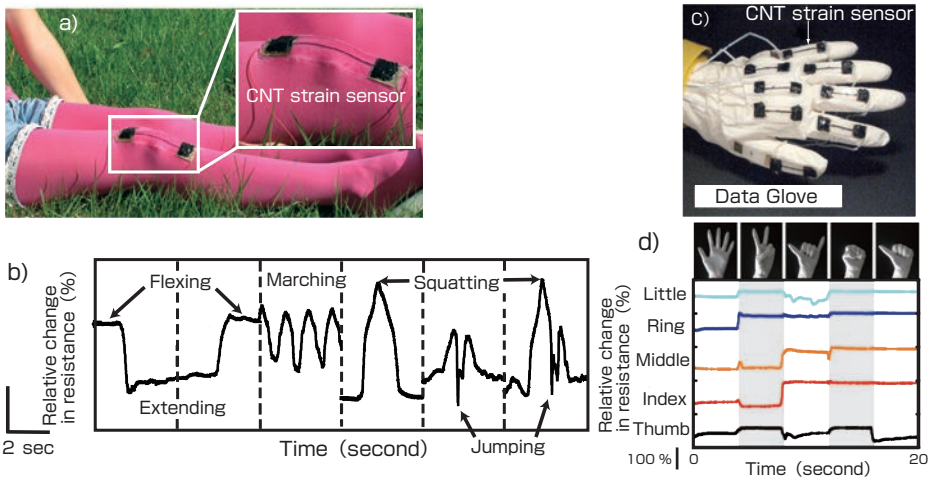
# A carbon nanotube strain sensor

## Detects 50 times as much strain as conventional strain sensors

We have developed a strain sensor using highly densely-packed, oriented single-walled carbon nanotube (CNT) films bonded to a stretchable polymer substrate. The sensor measures strain by detecting changes in the electrical resistance of the films. This CNT strain sensor can detect strains of up to 280 %, about 50-times greater than conventional metal strain sensors. In addition, durability was demonstrated by repeated application of 150 % strain over 10,000 cycles, and strain response time was found to be 14 ms. The sensor is less prone to creep than strain sensors made of conducting polymeric composites and is more than 20-times faster in creep recovery. The CNT strain sensor can be easily attached to clothing or directly to the body to monitor motion from knees to fingers. It is likely to be used in future wearable devices such as in recreational and medical applications.




Examples of human motion monitoring devices using the CNT strain sensor

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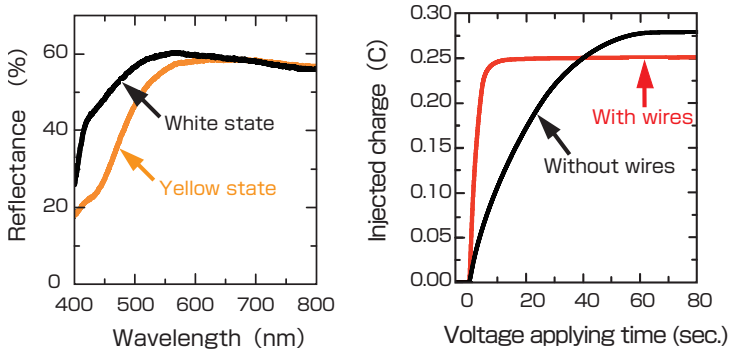
Nanotechnology, Materials and Manufacturing

# Improvement in performance of electrochromic devices through printing of fine metal wires

## A step toward larger-area light-control glass and electronic paper

Using the ink with the nanoparticles of Prussian blue-type complex, we have developed electrochromic devices by using a transparent electrode onto which fine metal wires have been printed. The devices realize high transmittance and reflectance without lowering response speed. The electrochromic device also reduces the amount of the rare metal, indium.

The fine metal wires were formed by printing with gold nanoparticle ink using the super inkjet method, an original technology of AIST. The developed electrochromic devices display a color change from white to yellow when a voltage of 1.5 V or less is applied. When white, the reflectance exceeds 55 % in most of the visible light region. The realized response speed is approximately eight times higher than when fine metal wires are not applied. No significant drop in speed was observed even after 1,000 cycles. This technology is expected to be effective in the production of larger area light-control glass, electronic paper, and other devices using electrochromic devices.




**Properties of the device with fine metal wires**
Changes in reflectance (left) and charge injection behavior (right)

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AIST TODAY Vol.11 No.9 p.10 (2011)

# Expansion of pitch calibration range of one dimensional grating standard

## The minimum pitch extended to 23 nm

One-dimensional (1D) gratings are one of the most important transfer standards for nanometrological instruments. National Metrology Institute of Japan (NMIJ) of AIST developed metrological atomic force microscopes (AFMs) and has supplied pitch calibration services (minimum pitch: 50 nm). Furthermore, a pitch calibration system based on the JCSS (Japan Calibration Service System) was also constructed with Japan Quality Assurance organization (JQA). JQA supplies pitch calibration services (minimum pitch: 97 nm) and the number of calibrations are a few hundred per year. Industry, however, requires calibration services for increasingly smaller pitches. This time, NMIJ has developed 1D gratings consisting of multilayer thin films and calibrated them. Furthermore, NMIJ conducted comparison measurements with the national metrology institute of Germany (PTB) using their own metrological AFMs. Based on the comparison results, NMIJ has expanded the minimum pitch calibration range to 23 nm. In the near future, the pitch calibration range of the JQA will be also expanded.

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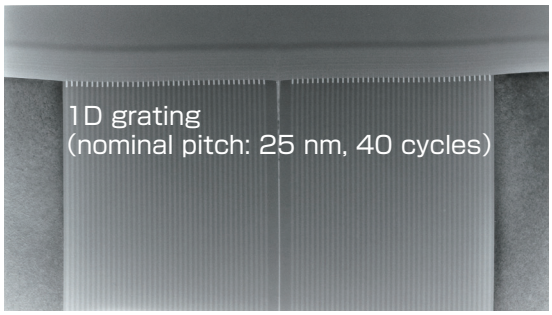


Transmission electron microscope image of the 1D grating (nominal pitch: 25 nm, cycles: 40) consisting of $Si/SiO_2$ multilayer structures
The 1D grating has two scale areas, area 1 and area 2.



# Thermophysical property measurement for gases using an acoustic technique

## Development of the apparatuses for acoustic resonance measurement with a spherical and a cylindrical cavity

Sound waves can be used for measurement of thermophysical properties for fluids. The author developed apparatuses for acoustic resonance measurement with a spherical and a cylindrical cavity to measure thermophysical properties of gas samples. In the spherical cavity, acoustic resonance frequencies can be accurately measured so that speed-of-sound of gas samples can be also accurately determined. Speed-of-sound is one of the thermodynamic properties related to density and compressibility, and is useful information to develop the thermodynamic equations of state for fluids. Recently, the author measured speed-of-sound for refrigerants with very low global warming potential, contributing to the development of the equations of state for them which are required to evaluate the cycle performance of the air-conditioning system. On the other hand, the half-width of acoustic resonances can be accurately measured using the cylindrical cavity, leading to obtain viscosity and thermal conductivity of gas samples. In the future, the author plans to accurately measure speed-of-sound of mono-atomic gas samples to derive the thermodynamic temperature, and reevaluate the international temperature scale (ITS-90).

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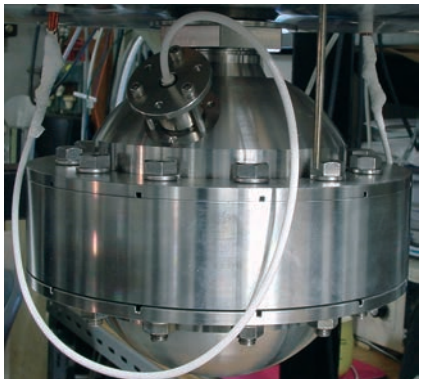

The apparatus for acoustic resonance measurement with a spherical cavity, which enables accurate speed-of-sound measurement for gas samples

## Hand-over Ceremony of the Pilot Plant for Biofuels from Non-food Biomass

Hand-over Ceremony of the Pilot Plant was held at Thailand Institute of Scientific and Technological Research (TISTR) located in the Thailand Science Park on May 19, 2011, in the presence of Minister Virachai Virameteekul, Ministry of Science and Technology of Thailand, and Japanese Ambassador Kojima. This plant was completed under the collaborative research for Innovation on Production and Automotive Utilization of Biofuels from Non-food Biomass, which is the program of Science and Technology Research Partnership for Sustainable Development of Japan International Cooperation Agency (JICA) and Japan Science and Technology Agency (JST).

Attendee (from third from left, AIST Vice-President Yamazaki, Science and Technology Minister Virachai, TISTR Governor Kasemsri, Japanese Ambassador Kojima and NSTDA President Thaweesak)

Five institutions, namely AIST, Waseda University, National Science and Technology Development Agency of Thailand (NSTDA), TISTR and King Mongkut's University of Technology North Bangkok, are carrying out this project, and they are implementing experimental studies of biofuels from non-food biomass, utilizing a pilot plant for automobile fuels from jatropha curcas. Human resource development of young Thai researchers, promotion of technology transfer and standardization of biodiesel fuels in Asia are also being carried out in this project.

## Party of Bandung Institute of Technology, Indonesia, Headed by Rector Akhmaloka Visit AIST Tsukuba

The six members of Bandung Institute of Technology (ITB) led by Rector Akhmaloka visited Tsukuba Central 7 and had a talk with AIST Vice-President Yamazaki and Director Wakita of the Geoinformation Center, AIST.

ITB Rector Akhmaloka (middle, front row) and Vice-President Yamazaki (left, front row)

The party was comprised of ITB Rector Akhmaloka, Vice Rector Abidin, Vice Rector Irwati, Prof. Sude and two researchers, graduates of ITB presently belonging to a Japanese university and institute. Dr. Saepuloh Asep of AIST, also a graduate of ITB, led the party as their guide.

The party headed by Rector Akhmaloka arrived in Japan on June 10 to attend the science and technology workshop held by Indonesian and Japanese institutions every year, and they visited AIST after visiting Japan Atomic Energy Agency in Tokai village.

Following the introduction about AIST given by Vice-President Yamazaki, Rector Akhmaloka also gave a general description of ITB. In addition, Director Wakita of the Geoinformation Center gave a report of the research activities in the fields of geology, and Dr. Saepuloh Asep gave a report of the analysis of volcanic activities based on satellite data.

Since there are many earthquakes and volcanic disasters in Indonesia as there are in Japan, Rector Akhmaloka asked for collaborative research with AIST for the mitigation of earthquake and volcanic disasters in addition to petroleum and mineral exploration and marine geological survey.

AIST has been already active in collaborative research with Indonesia. For example, the Agency for the Assessment and Application of Technology (BPPT) and AIST concluded a comprehensive MOU on research cooperation. With this visit, further collaboration in research related to the geological fields including seismological and volcanic research is expected.

**Cover Photos**
Above: Outer appearance of the integrated flexible CIGS submodule (p.9)
Below: Various types of organic thin-film solar cell submodules providing excellent design flexibility (p. 12)

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