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.

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Research Center for Photovoltaic Technologies
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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).

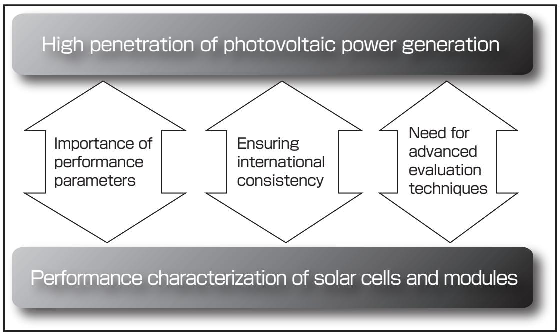


Fig. 1 Importance of photovoltaic devices characterization technologies

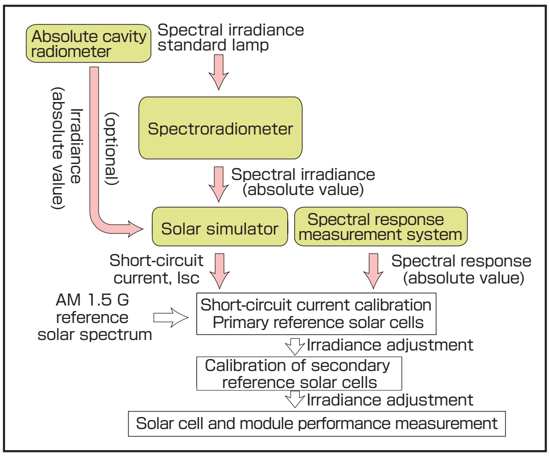


Fig. 2 Flow of calibration of reference solar cells and performance characterization of solar cells and modules

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

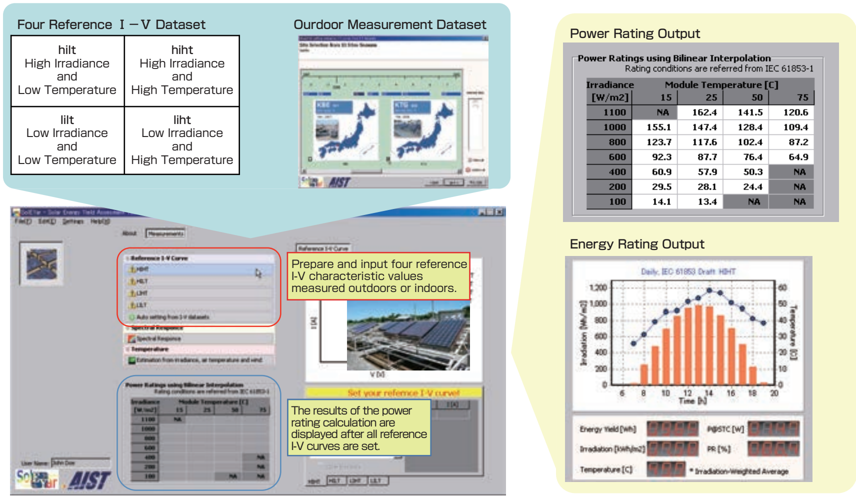
An energy rating is the measurement and evaluation method that can determine which solar cells among various types generate the largest output power (energy) in a certain period.

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.

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Addressing Issues Related to Operating and Maintaining Photovoltaic Systems

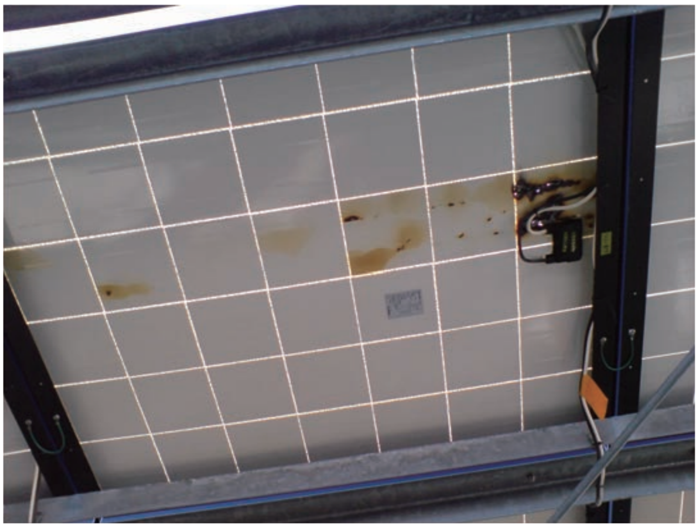
Maintenance-free myth about photovoltaic systems?

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.

Automated crystalline silicon solar cell tabbing and string system | Large vacuum laminator | Solar simulator | Environmental test chamber

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.

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Development of CIGS Solar Cell Technology (High-Functionality, High-Performance Flexible Submodule)

Characteristics of CIGS solar cells

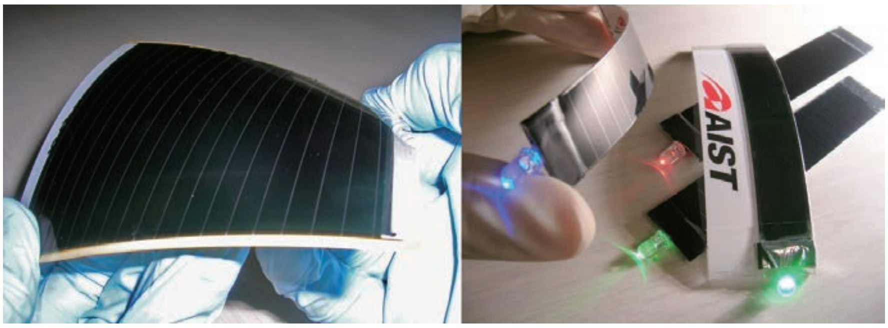
CIGS is one of the I-III-VI_2 compound semiconductors composed of the I-group element copper (Cu), the III-group elements indium (In) and gallium (Ga), and the VI-group element selenium (Se). Specifically, it is expressed by the formula $Cu(In_{1-x}Ga_x)Se_2$ ($0 \leq x \leq 1$). Solar cells using CIGS 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.

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).



Outer appearance of the integrated flexible CIGS submodule

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.

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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.

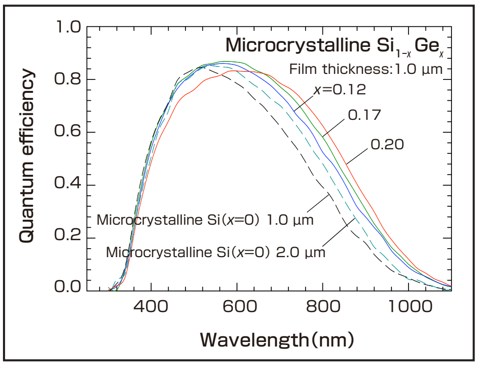

Fig. 1 Quantum efficiency spectrum of microcrystalline SiGe solar cells with different Ge content (x) (solid lines)
The microcrystalline SiGe solar cells are half as thick as microcrystalline Si solar cells (dashed lines) but have higher infrared absorption sensitivity.

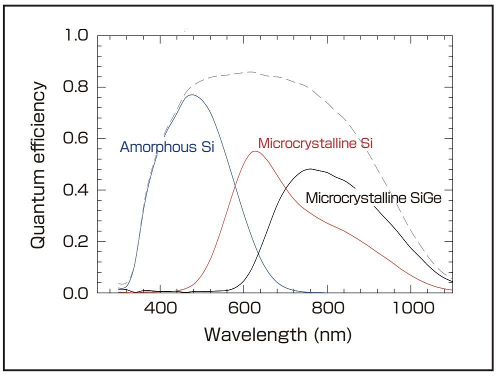

Fig. 2 Quantum efficiency spectrum of the fabricated triple-junction solar cells
The solar cells generate power by absorbing the solar spectrum over a wide range through the use of three materials having different wavelength sensitivities (band gaps).

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.

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Reference

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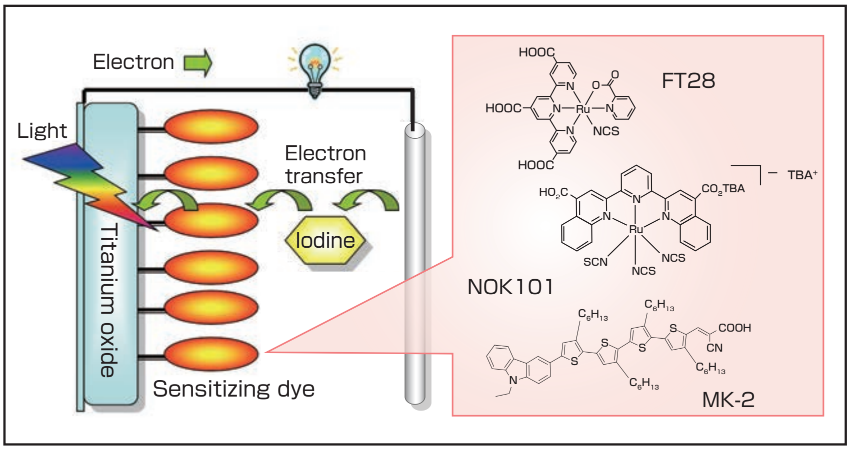
Dye-Sensitized Solar Cells

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.

Energy Technology Research Institute
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Nagatoshi KOUMURA

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[1] PCT/JP2007/056383
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Development of Organic Thin-Film Solar Cells

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.

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.

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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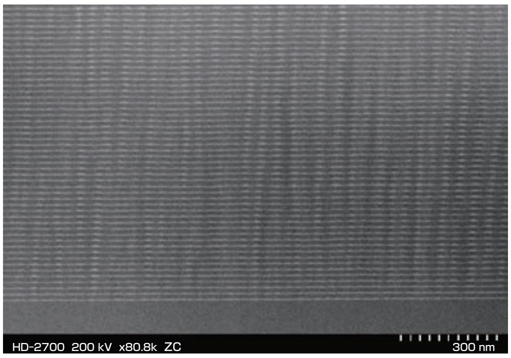
Development of Innovative Solar Cells

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.

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