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Technology Conference Report

Future perspectives on photovoltaics

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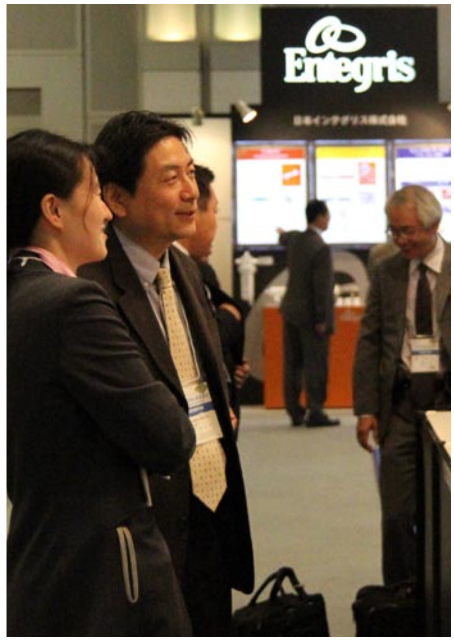


Speakers

Alan J. Heeger	University of California
Katsuhiko Shirasawa	KYOCERA Corporation
Sadao Wasaka	NEDO
Antonio Luque	Universidad Politécnica de Madrid
Michael Grätzel	EPFL
Yoshitaka Okada	The University of Tokyo
Joachim Luther	SERIS
Tatsuya Takamoto	SHARP Corporation
Michio Kondo	AIST
Wim Sinke	ECN
Kazuo Nakajima	Kyoto University
Makoto Tanaka	SANYO Electric Co.
Hiroshi Komiyama	Mitsubishi Research Institute
Mitsuo Inoue	Mitsubishi Electric Corporation
Koichi Yamada	Japan Science and Technology agency
Atsushi Masuda	AIST
Ryne Raffaelle	NREL
Katsumi Kushiya	Solar Frontier K.K.
Hiroo Konishi	NTT Facilities
Osamu Ikki	RTS Corporation

Entering the gigawatt era

Soaring growth in production capacity and a plethora of emerging alternative cell technologies are two characteristics of the solar energy sector that came across particularly strongly at the recent Nature Photonics Technology Conference 'Future Perspectives on Photovoltaics'. The three-day event, held in October 2010 in Tokyo, Japan, brought together experts from around the world to discuss the current status and future outlook of the photovoltaic sector. It became clear at the conference that the market dominance of crystalline silicon, despite its impressive improvements in performance, may soon be challenged by alternative and potentially lower-cost technologies such as thin-film Si, CIGS, CdTe, polymer cells and dye-sensitized cells. Many research opportunities still exist, however, particularly at the level of quantum engineering, for example in the construction of viable intermediate-band cells, the fabrication of bandgap-optimized materials for improved multijunction cells and the use of photonic structures to successfully trap light and minimize optical losses. This short report offers a summary of some of the opinions expressed about various photovoltaic technologies at the conference, interviews with several speakers and a round-up of what was on show at the exhibition. Finally, I would like to thank our co-organizers Impress R&D, Makoto Konagai from the Tokyo Institute of Technology and all the members of the technical advisory board, as well as our sponsors and exhibitors for all their support in ensuring that the event was a success.

Oliver Graydon

Editor, *Nature Photonics*

Conference report

Solar energy is looking more attractive than ever, thanks to significant improvements in the performance of silicon photovoltaic cells and the emergence of a wide variety of alternative material systems.

Ever since the demonstration of the first working silicon solar cell by Pearson, Chapin and Fuller at Bell Labs in the USA in the 1950s, the dream of harnessing the Sun's power to generate electricity has inspired scientists to develop photovoltaic technology. Now, fifty years later, as nations around the world establish their energy generation plans for the twenty-first century and prioritize how to reduce the impact of fossil fuels on the environment, it seems certain that solar energy is going to play an increasingly important role in many regions across the globe. Indeed, installations of giant gigawatt-scale solar farms have already begun, with the next big challenge being to introduce photovoltaic technology to buildings and homes on a wide scale.

So why has the widespread deployment of solar-cell technology on residential properties taken so long? The answer is simply a matter of high cost and low efficiency. Many experts now believe, however, that the optimization of silicon technology and the slew of low-cost alternatives, including thin-film, polymer and dye-sensitized cells, have together made the mass deployment of solar cells a compelling proposition.

"The solar industry used to comprise just 10–20 companies. Now it exceeds 200," explained Osamu Ikki, president of the RTS Corporation in Japan. "We are now entering the era of gigawatt production. Over the next ten years, gigawatt-level plants will achieve mass-production, and module prices will fall below 100 yen per watt."

Similar optimism was expressed by speakers from the USA. "We are now entering an era of wide-scale deployment. The latest growth prediction is 65% for 2010," commented Ryne Raffaelle, director of the National Center for Photovoltaics at the National Renewable Energy Laboratory (NREL) in Colorado, USA. "If you look at the best technologies, cell efficiency has effectively been growing at 1% a year for 30 years."

Indeed, market statistics show that the industry has been climbing exponentially in terms of production volume. According to figures from the industry magazine PV News, worldwide photovoltaic production almost tripled from 3,746 MW in 2007 to 10,660 MW in 2009, with even higher figures expected for 2010. The cumulative installed capacity of Japan alone is expected to grow by an order of magnitude over the next decade, from 2.6 GW in 2009 to 28 GW by 2020, finally reaching 53 GW by 2030. This growth is fuelled by Japan's long-term energy plans such as PV 2030, PV 2030+ and Cool Earth 50, formulated by the New Energy and Industrial Technology Development Organization (NEDO). According to Sadao Wasaka, executive director of NEDO, the aim is to reach a photovoltaic energy generation cost of ¥14 kWh^{-1} by 2020, and just ¥7 kWh^{-1} — on par with nuclear power — by 2030, through improvements to the technology and manufacturing techniques.

From a technological point of view, there is no doubt that tremendous progress has already been seen over the past fifty years. Although the first Bell Labs prototype cell in 1954 offered a conversion efficiency of only around 5%, today's best commercial crystalline silicon cells now offer efficiencies of 22–24%.

And it's not only crystalline silicon technology that has improved over time. There has also been an explosion in the exploration of new technologies and material systems, including dye-sensitized cells, organic polymer cells and multijunction cells based on compound semiconductors, as well as the emergence of thin-film silicon and copper–indium–gallium diselenide (CIGS) and CdTe systems. Multijunction cells have now reached an amazing conversion efficiency of 40% under small-area concentrated sunlight conditions.

In October 2010, *Nature Photonics* brought together 20 experts from around the world to discuss the current status and prospects of these various photovoltaic technologies. Here's a summary of what was discussed, grouped by technology area.

Polymer solar cells

Alan Heeger from the University of California at Santa Barbara in the USA and co-founder of the polymer solar cell developer Konarka began his keynote speech on plastic solar cells by flexing and throwing a thin plastic solar cell to demonstrate its low weight and robustness. He explained that the field of polymer solar cells originates from the discovery of ultrafast (~50 fs) photo-induced electron transfer between a light-absorbing semiconducting polymer and a fullerene. This discovery rapidly led to the development of 'bulk heterojunctions' — solar cells based on a polymer–fullerene mix in the form of an interconnected network — which today have reached efficiencies of around 8% and are now being commercialized by firms such as Konarka and Solarmer. One of the important benefits of this technology is that it is processed in solution form, making it compatible with roll-to-roll printing on a plastic substrate — a low-cost, mass-production process. The combination of low cost and high flexibility could help polymer solar cells to reach applications that are not suited to rigid and expensive silicon technology. Because these cells are not only semitransparent but also insensitive to the angle of incident sunlight, one of their most promising applications is for use in power-generating windows. Heeger says that production speeds of 30 feet per minute for 1.5-m-wide films have now been achieved, and believes that polymer cells will surpass efficiencies of around 10% before 2015.

Dye-sensitized solar cells

Another potentially low-cost solar-cell technology that can be manufactured through a print process is the dye-sensitized solar cell, or Grätzel cell, named after its inventor Michael Grätzel from École Polytechnique Fédérale de Lausanne in Switzerland. First described in *Nature* in 1991, the dye-sensitized solar cell combines a light-absorbing dye with a nanostructured porous layer of titanium dioxide and liquid/gel electrolyte to transport electrons and holes out of the cell.

"This is the only type of solar cell to use molecular absorption, thereby mimicking natural photosynthesis," explained Grätzel in a presentation on the topic. "Light absorption and charge transport are decoupled in this technique, and this flexibility means that that light absorption can be performed by dyes, or alternatively by quantum dots."

Dye-sensitized solar cells are now reaching conversion efficiencies of around 12% in the laboratory, and, thanks to the development of new broadband dyes and electrolytes, Grätzel believes that efficiencies of 15% are just around the corner.

As with polymer solar cells, the attraction of this technology is the low cost of the print-based fabrication approach. An important additional benefit of dye-sensitized solar cells is that they also work well under indoor artificial lighting conditions, suggesting that this technology will probably find use as a convenient power source for interior portable devices.

One of the initial concerns about dye-sensitized solar cells was the practicality of using a liquid electrolyte, but the development of suitable gels seems to have resolved this issue.

Wafer silicon

Several speakers made the important point that existing photovoltaic technology, particularly wafer (monocrystalline) silicon, has already matured to reach high performance levels, and that we don't necessarily need new technologies or higher efficiencies for solar cells to become a great success. Instead, the pressing issue is simply one of bringing down costs. "Price reduction is the key," commented Joachim Luther, CEO of the SERIS solar institute in Singapore. "The question is how to reduce costs."

Wim Sinke from the Energy Research Centre of the Netherlands made a similar point in regard to the strengths of wafer silicon technology. Sinke explained that we already have half a century of manufacturing experience and a huge technology base of processes and device designs for manufacturing wafer silicon. Furthermore, wafer silicon has an extensive track record in performance and reliability, boasting the highest power conversion efficiency for all large-area cell technologies (except multijunction cells, which are used in small areas with solar concentrators).

The fundamental Shockley–Queisser limit for single-junction silicon cell operation yields a theoretical maximum efficiency of around 30%, with laboratory- and commercial-scale silicon cells already approaching this number. Indeed, the best laboratory-scale monocrystalline silicon cell efficiency of 25% was demonstrated in 1999 by Martin Green at the University of New South Wales in Australia. Today's commercial cells from firms such as Sunpower and Sanyo are now only a few percent behind this figure.

Sinke also commented that there are several further opportunities for improving wafer silicon cell technology, including minimizing recombination (the unwanted decay/loss of photo-excited charge) by improving material quality through better management of impurities and defects; minimizing optical losses by reducing reflections and employing light-trapping technologies such as plasmonic structures; and minimizing electrical resistive losses through advanced electrode technologies.

Thin-film cells

Katsumi Kushiya from Solar Frontier gave an update on the current status of thin-film solar cells based on CIS/CIGS. Unlike crystalline silicon, the layer of active material in a thin-film solar cell only needs to be 1–2 μm thick, owing to its very strong optical absorption.

CIS cells have been successfully commercialized by many firms in conjunction with various universities, including Würth Solar, Solibro, Miasole, Nanosolar, Avancis, Solar Frontier and Honda Soltec. Kushiya said that the race is now on to increase the efficiency of commercial modules from 14% to 16%. By 2010, Solar Frontier expects to have established a 1 GW annual production capacity for fabricating CIS cells. Michio Kondo, director of the Research Center for Photovoltaics at the National Institute of Advanced Industrial Science and Technology (AIST) in Japan commented that the CIGS submodules fabricated at AIST have now reached efficiencies of 15.9% for a 10 cm × 10 cm area comprising 17 cells. Kondo explained that there is much interest in increasing the efficiency of thin-film devices using multijunction designs made from a variety of materials, such as Si–Ge, CGS, CIGS and CIS. Other research opportunities include the investigation of new materials such as wide-bandgap systems (SnO, CIGSSe and CGS), nanostructures such as InGaAs quantum dots or carbon nanotubes, and single-crystalline organic materials. Another successful thin-film material systems is CdTe, which First Solar is now deploying on a wide scale.

Intermediate-band cells

Antonio Luque from the Instituto de Energia Solar at the Univerisdad Politécnica de Madrid in Spain and Yoshitaka Okada from the University of Tokyo both gave presentations on the concept and current status of intermediate-band solar cells. The principle idea, as first proposed by Luque in 1997, is that conventional solar cells based on a single-band transition (valence to conduction band) suffer from an inherent compromise. Put simply, solar cells aim to generate as much power as possible from any incident light, which in turn means simultaneously wanting the highest possible open-circuit

voltage and short-circuit current density. The problem is that the former rises with increasing bandgap while the latter falls, meaning that a compromise must always be found between these two competing factors. The idea of an intermediate-band cell is to introduce a partially filled band between the valence and conduction bands, thereby simultaneously providing the cell with both a large and small bandgap. The intermediate band essentially functions as a relay point, allowing lower-energy (longer wavelength) photons to excite electrons from the valence band to the intermediate band, followed by a second transition to the conduction band. At the same time, higher-energy (shorter wavelength) photons are still able to excite electrons directly from the valence band to the conduction band as usual. Intermediate-band cells therefore offer theoretically higher conversion efficiencies than conventional cells because lower-energy photons can also be put to use. Indeed, calculations suggest that values as large as 47% under one sun and 67% under concentrated sunlight are theoretically possible.

"The solar industry used to comprise just 10–20 companies. Now it exceeds 200."
Osamu Ikki, RTS

The technology for fabricating intermediate-band solar cells is still in its infancy. Scientists have recently demonstrated the principle of intermediate-band solar cells in a bulk ZnTe:O cell design, although still at low efficiencies. The most promising approach seems to be the use of quantum dots (semiconductor nanocrystals that can have their bandgap artificially engineered by controlling their size). The idea is to 'sandwich' such quantum dots, which together serve as a custom-engineered intermediate band, within a conventional p–n junction solar cell. There are, however, many technical hurdles to be overcome before an intermediate-band solar cell with an advantageous efficiency can be realized. The principal problem is related to the dynamics of the energy level structure in an intermediate-band solar cell. In particular, the desired transition between the intermediate band and the conduction band tends to occur at a low rate, whereas unwanted recombination between the intermediate band and the valence band tends to occur relatively often. As a result, electrons that are successfully excited to the intermediate band from the valence band often escape from the quantum dots by thermal or field-assisted tunnelling. However, Okada commented that the use of a strain-compensated growth technique is proving effective for making InAs/GaNAs quantum dot superlattices. A 100-layer stack of such a structure has an optical absorption of around 20%, and transitions between the intermediate band and the conduction band have now been observed at room temperature under light from the solar spectrum. Research is now pursuing the development of smaller sizes and higher densities of quantum dots, which should lead to increased absorption and compatibility with concentrated sunlight.

Multijunction cells

Many of the speakers at the conference discussed the merits and performance of multijunction solar cells. The well-proven design behind multijunction solar cells exploits a stack of p–n junctions, each made from a different set of semiconductors and thus each offering a distinct bandgap and spectral absorption profile to cover as much of the solar spectrum as possible. Usually either two ('tandem') or three ('triple') junctions are used. Given the expense and difficulty in their fabrication, multijunction cells are often used in small-area cells operating under concentrated sunlight or in space applications. Commercial devices manufactured by Sharp, Emcore, Spectrolab and Azur have efficiencies of around 35% — significantly higher than single-junction devices. Koichi Yamada, deputy director-general of the Center for Low Carbon Society Strategy at the Japan Science and Technology Agency, commented that a triple-junction cell with bandgaps of 0.74, 1.2 and 1.8 eV would have a theoretical efficiency of 59%. In practice, however, the most commonly employed materials are Ge (0.67 eV), GaAs or InGaAs (1.4 eV), and InGaP (1.85 eV). There is therefore strong motivation to find a new higher-bandgap material to replace Ge and a new lower-bandgap material to replace GaAs. In 2010, by optimizing its cell design and employing InGaP, GaAs and InGAaS for the top, middle and bottom junctions, respectively, Sharp reported the world's highest conversion efficiency for a triple-junction solar cell, providing 42.1% at 230 suns and 35.8% under one-sun illumination. In October 2010, just a few days before the *Nature Photonics* conference began, Spire Semiconductor in the USA claimed to have achieved a new triple-junction cell efficiency of 42.3% under 420 suns.

"Who holds the current world record for efficiency? NREL, Fraunhofer, Emcore, Spectrolab and Spire have all demonstrated efficiencies of over 40%, with numbers differing by much less than the error bars of the measurements, and often being performed at different laboratories with different simulators," commented Raffaelle from NREL. "Verifying efficiencies of over 40%, especially under concentration or with quantum-confined materials or advanced photonic structures, demands unprecedented fidelity on solar simulation and measurement protocols."

Efficiencies can of course be increased by using more than three stacked junctions. Yamada and Raffaelle both commented that although this is theoretically possible, it is far from straightforward. "Increasing the number of cell layers is an effective way of improving efficiency. However, the mismatch of the lattice constant limits the combinations," commented Yamada. "Developing the processes for preparing new materials and forming junctions are important."

To address this need, researchers at the University of Tokyo are developing a new four-junction material based on strain-compensated compound semiconductors with a bandgap of around 1 eV. In principle, a multijunction cell comprising AlInGaP (2.0 eV), InGaAs (1.4 eV), Ge (0.67 eV) and this new material (1 eV) could yield a four-junction solar cell with a theoretical efficiency of up to 52%.

Raffaelle has a pragmatic opinion about the prospects of using more than three bandgaps to improve efficiencies beyond 50%. "Thermodynamically it can done; practically speaking, probably not." ■

Lightweight, low-cost organic approach

A new and exciting technology that can produce lightweight, flexible, low-cost solar cells in large quantities from organic semiconducting polymers has a strong future in the field of photovoltaics, says Alan Heeger from the University of California at Santa Barbara in the USA.

Alan Heeger foresees that the low-cost roll-to-roll manufacturing of polymer solar cells may allow them to succeed where other solar-cell technologies have failed.

What is a polymer solar cell and why is it attractive?

It's a new idea, and new ideas are always exciting. The polymer solar cell is a new concept that will allow us to convert sunlight to electricity using semiconducting polymer materials. Mixing semiconducting polymers with suitable acceptors allows ultrafast photo-induced electron transfer to be achieved. This method is capable, in principle, of very large-area, fast and low-cost production, which makes it very exciting. However, the science is still not completely understood. There are major challenges that I am enjoying working on and that people all over the world are currently engaged in.

What do you think are the biggest challenges facing polymer solar-cell technology today?

Of course, there are challenges. We need to improve the efficiency, and already understand why the efficiency is currently in the range of 7–8%. We know that we have to create new materials that have absorption bands mimicking those of silicon. We also have to absorb solar radiation from the infrared wavelength range. We understand that we have to tune the energy levels of both the donors and acceptors to achieve a higher open-circuit voltage. We understand we have to minimize recombination to get a higher fill factor. However, understanding is not the same as doing. In an ideal system, all of these things must be achieved at the same time. When we do that, I am confident that higher efficiency can be achieved. Cost is also a serious challenge. We can already fabricate polymer solar cells, although currently only as a demonstration, not as a commercial product. However, we foresee the ability to make polymer solar cells in large areas at high throughput. On the other hand, roll-to-roll coating is inherently a low-cost manufacturing process. The highest efficiencies of 7–8% were achieved by a company in the USA called Konarka. Konarka has a roll-to-roll manufacturing facility that is being developed for product introduction, and the company has demonstrated that this process is scalable. That in itself is exciting. Over the past 3–4 years, we've only been able to make small devices at very low efficiencies. Now we are able to fabricate devices measuring many square metres. I think there is a real future here, and we are all working hard to make it happen.

Do you believe we have reached the maximum cell efficiency?

We have certainly not reached the maximum. The materials are not optimum for the applications, and there have been some very serious analyses of the potential for this field. The basic physics of polymer solar cells is essentially the same as that of inorganic solar cells. The prediction is that we should be able to achieve a cell efficiency of 15–20%. Indeed, we have a specific example in which that kind of efficiency at wavelengths within the absorption band has been demonstrated. But the challenges are to get the absorption band right, and to achieve a self-assembly process that will enable charge collection. Photo-induced electron transfer gives a very high yield of charge separation — that is the foundation on which the whole field is built.

Do you see this technology dramatically coming down in price over the next five years? What could help make this happen?

It's always dangerous to predict the future; creating the future is a better idea. It's clear from what I have seen that there are significant opportunities for reducing the cost from what we have today, but this is a great challenge. I am confident that the cost will come down when we get the efficiency into the range of 10% or greater. I think the actual cost will be very low by then. As we heard in the conference, the cost of installation and the cost of the inverter all come into the total cost of the solar cell. Although the goal of getting the cost down to an acceptable level involves many challenges, I believe that polymer solar cells will be a low-cost technology in the future.

How do you expect the market share of polymer solar cells to look in 5–10 years time?

This is a question that I am not equipped to answer. We see many unique opportunities at the moment. Lightweight, flexible, rugged technology provides opportunities in developing countries for relatively small power generation in individual houses, which could change the lives of billions of people. Semi-transparent solar cells for use in windows and building-integrated applications are also major opportunities. The fact that we can achieve significant power generation even under tungsten light demonstrates that these devices can generate electricity even without direct sunlight. Polymer solar cells therefore have many applications and many advantages over today's leading technologies. I am sure there will be opportunities in which polymer solar cells can flourish. For example, lightweight structures that cannot support heavy silicon solar-cell panels could support polymer solar cells, which can be easily removed at a later date.

Interview by Rachel Won

Intermediate-band boost

First proposed in 1997, the intermediate-band solar cell has attracted significant attention from the photovoltaic community for its potentially very high efficiency, says Antonio Luque from Universidad Politécnica de Madrid in Spain.

Antonio Luque expects that intermediate-band solar cells will come to fruition after 2030, with important applications arriving by 2050.

What is an intermediate-band solar cell and why is it attractive?

The intermediate-band solar cell uses a material that has an additional permitted band within the main bandgap of the semiconductor. This additional band can be achieved through several methods, such as the addition of impurities, which leads to deeper energy levels, or by introducing quantum dots and then using their energy levels as the intermediate band. In principle, this intermediate band allows you to produce additional current by using lower-energy photons that cannot directly pump electrons from the valence band to the conduction band; instead, two small lower-energy photons can use the intermediate band as a 'relay' for the current. The nice thing is that it should be possible to produce voltages higher than the energy of the photons you are using. Of course, more than one photon is required, but in principle you can extract the energy at a voltage above the photon energy. The maximum efficiency of this concept is 63%, whereas for ordinary solar cells using the same hypothesis the thermodynamic limit is 40%. This concept is therefore attractive because it allows for potentially very high efficiency, although getting close to the thermodynamic limit will be very difficult.

What is the highest efficiency reached so far, and how much higher could it rise?

Today, the best efficiency is 18%. In 20–30 years from now, the efficiency could reach 50% by using two cells in tandem; the thermodynamic limit is 72% in such a set-up. If we apply the same 'efficiency rule' used for triple junction cells — that the maximum efficiency is two-thirds of its thermodynamic limit — I think we could reach efficiencies of 50%.

What is the biggest challenge for this technology?

The biggest challenge today is still to understand how the cell works. We believe that the sub-bandgap light is quite well-absorbed, but only a small part of it is converted into current. Although we explain this as recombination, 'recombination' is just a word — we don't yet understand the specific mechanisms that prevent the extraction of the mode current. This is the main challenge to be tackled over the next five years. I hope that by 2015 the intermediate-band solar cell will be well-understood, even if we are still using unoptimized structures and therefore still at low efficiencies. At the moment we are only using structures that are good for our research, such as InAs quantum dots in GaAs.

Is cost one of the challenges?

It is too early to talk about cost. There are two potential ways of applying this cell. One will be in concentrators, just like for multi-junction solar cells, in which case the cost of the device becomes very small because very little material is needed. Such a potentially high efficiency — in the range of 45–50% — means the cost of the tiny cell doesn't matter very much. The other option is to use it in the fabrication of thin-film solar cells together with other thin-film concepts. For example, it would be relatively cheap to put titanium or even quantum dots in such a structure. If this concept is to be successful — which it might — you could increase the efficiency of these intermediate-band solar cells from 20% to 25–28%. The cost of making the whole cell would not change much as such additional processes are relatively cheap. Although these cells face the same cost issues as all other solar cell technologies, intermediate-band solar cells can provide higher efficiency at almost the same cost.

What do you think the photovoltaic industry will look like in 5–10 years time?

Over the next 10 years, I predict the proportion of the world's energy generated by photovoltaics will rise to around 2%. I believe the intermediate-band solar cell will start to be industrialized in 2020, but will still comprise only a small fraction of photovoltaic technology. The intermediate-band solar cell will truly come to fruition after 2030. It may become a serious contender to other technologies by 2050 if the efficiency reaches the level I mentioned earlier, but probably not by 2020. In general, photovoltaic technology needs to have a fast learning curve. The good thing is that photovoltaic devices are based on twenty-first century science and technology. By the end of the century, I expect photovoltaic technology to become the main provider of the world's electricity — that is what we are aiming towards with our intermediate-band solar cell.

Interview by Rachel Won

New dyes, new opportunities

Joint efforts within the research community to develop innovative dyes will provide dye-sensitized solar cells with many new opportunities, explains Michael Grätzel from École Polytechnique Fédérale de Lausanne in Switzerland.

What is a dye-sensitized solar cell and why is it attractive?

The dye-sensitized solar cell is the only solar cell that mimics the photosynthesis process in a green leaf. It uses molecules as sensitizers or dyes, just like the leaf does with chlorophyll molecules, which absorb light and use it to generate electric charge. This reaction is entirely mimicked by the dye-sensitized solar cell. The difference, however, is that in the green leaf the charges are immediately converted into energy by the plant, whereas in dye-sensitized solar cells the electric charges are drawn out to make a photovoltaic device.

What do you think are the biggest challenges facing dye-sensitized solar-cell technology today?

The dye-sensitized solar cell has achieved a module efficiency of over 10%. This remarkable figure was achieved through small-laboratory cell research, and we've already reached efficiencies of up to 12%. The losses are very small, which is quite unusual. This shows that the fabrication of dye-sensitized solar cells can easily be scaled up. The challenge in the research community now is to increase this 12% efficiency to over 15% or 20%. The higher the efficiency, the more competitive the cell will be. As there is strong competition from other solar-cell technologies, the dye-sensitized solar cell must be competitive in terms of price, capability and conversion efficiency. Fortunately, this solar cell has specific applications that are unachievable using other photovoltaic technologies. For example, it is the only solar cell that can be made into transparent glass while being used as an electric power source — this is something that other silicon or thin-film photovoltaic technologies cannot offer. We foresee many opportunities in the design of buildings and other creative applications. There are also other applications that would benefit from the flexible, lightweight configuration of the dye-sensitized solar cell, such as for charging mobile telephones. This is certainly very attractive, and sales in the marketplace have started with this kind of product.

Michael Grätzel points out that the dye-sensitized solar cell has to be competitive in terms of price and conversion efficiency to rival other solar-cell technologies.

Do you believe we have reached the maximum cell efficiency?

The recent discovery of a new dye by the Segawa group at the University of Tokyo has revolutionized the whole field. The photocurrent response curve of this dye looks like silicon, capturing the whole visible spectrum up to 1,000 nm and converting about 90% of the photocurrent into electric current. This shows that it is possible to fabricate a dye-sensitized solar cell from a single dye, and it's an amazing demonstration of the power of this technology. To get efficiencies of over 15%, we need to use this type of dye to produce a high current. We also have to improve the output voltage of this technology. Fortunately there is an active research community working in this area, allowing new discoveries to be gathered from all around the world. If someone invents a new dye, he or she could become very prosperous by commercializing it. Unlike other photovoltaic technologies that have thousands of people working on a single material, we have a wide choice of materials and every new discovery can bring a jump in conversion efficiency. Whoever achieves the jump will be rewarded — that is the great thing about the dye-sensitized solar cell.

Has this cell been commercialized, and is the fabrication process difficult?

We have already started to commercialize the dye-sensitized solar cell with a company called G24 Innovations. The initial product — a solar-cell-equipped backpack — is selling very well. The Presidents of Germany and Switzerland visited us recently and were delighted to receive a backpack equipped with these flexible dye-sensitized solar cells for their next mountain excursion. I think the consumer will decide whether you have a nice product. For example, I am sure there is a market for the solar lampshade made by Sony, although this could be a niche application. The dye-sensitized solar cell is a technology that will find widespread use through niche applications.

How do you expect the photovoltaic sector to look, in terms of deployed technologies and market share, in 5–10 years time?

I think the dye-sensitized solar cell will face very strong competition from China because more than 50% of the solar cells produced in China are made from silicon. It will be difficult for the dye-sensitized solar cell to corner the market; there are always new materials in this type of solar cell. The market cannot easily be cornered by one individual with a single material. But by 2020, we will certainly see many more applications that use dye-sensitized solar cells, perhaps even in solar farm applications. However, I expect that solar farms will continue to be dominated by silicon panel cells. I don't think solar cells in general will dominate the renewable energy market; there is still a huge need for atomic energy, and I think there will be space for all technologies. It's not necessarily a cut-throat competition — what we really need is more cooperation to meet the energy challenges that all of us are facing.

Interview by Rachel Won

Upbeat silicon

Although crystalline silicon solar cells will dominate the market, thin-film cells have great prospects in terms of efficiency and cost, says Michio Kondo from the National Institute of Advanced Industrial Science and Technology in Japan.

Michio Kondo is positive about the future of the thin-film silicon solar cell.

How many different types of silicon solar cell are there?
There are two major types of silicon solar cell. One is wafer-based, bulk crystalline silicon solar cells, which can be categorized into single-crystalline and multicrystalline solar cells. This type of cell can be formed in a conventional sandwich structure or a back-contact structure. The other major type is thin-film silicon solar cells. There are also some other types of silicon solar cell, such as silicon-ball solar cells and concentrator-type solar cells. They are available but are not so popular.

Why are silicon solar cells attractive?
The greatest advantage of silicon solar cells is silicon's natural abundance and environmental friendliness, but the driving force behind silicon solar cell technology comes from its established and robust manufacturing technology.

What do you see as the biggest challenges today facing silicon solar cell technology?
From the technological point of view, the biggest challenge is to exceed the physical limit of the crystalline silicon solar cell, namely the 30% efficiency level, which is the limit for any single-junction solar cell. The industrial challenge is to reach a price of US$0.50 per watt for a solar module. This is comparable to the competing technologies. These are the big challenges of crystalline silicon solar cell technology. However, the challenge of thin-film silicon solar cells is more one of efficiency than cost.

What is the typical efficiency now? Have we reached the limit?
It depends on the technology. For crystalline silicon solar cells, the lowest range of module efficiency is around 12–13% and the highest is around 17–20%. If we want to achieve an efficiency of 20% in a crystalline silicon solar module, we need a cell efficiency of about 23%. At the moment, the highest efficiency in the laboratory cell is 25%. In this sense, the research-level solar cell has already reached the efficiency needed. However, many people argue that the practical limit of crystalline silicon solar cells can go up to about 28–29%.

You mentioned during your talk that people are expecting to see efficiencies of >40% in 2050. Is it going to take that long?
The short-term target is to get module efficiencies of 20% for crystalline silicon solar cells. I think this efficiency will become more common in the short term. In the long term, if crystalline-silicon-based solar cells cannot exceed the physical limit of 30%, I would be pessimistic about their future.

Do you see the technology drastically coming down in price over the next five years? What could help make this happen?
Yes, and I think thin-film technology will be of great help. I think that the efficiency and the manufacturing technology, including equipment and process control, will help reduce the manufacturing cost drastically. We will be able to achieve a cost of US$0.50–0.70 per watt for thin-film silicon modules, and the price of crystalline silicon solar cells will be around US1.00 per watt. It could be difficult for crystalline silicon solar cells to reach US$0.50 per watt in the next five years.

Do you think the emergence of new materials will help reduce the price?
Of course, in the long term, the answer is 'yes'. For example, silicon–germanium is an old material but thin films are a new technology. Its use will help improve the efficiency and reduce the cost. In the next five years, I think the multijunction, thin-film silicon solar cell is a realistic target.

In five to ten years' time, how do you see the sector for silicon solar cells looking in terms of deployed technologies?
This is a very big question. Even in the crystalline silicon solar cell, there are many different varieties of structure, for example back-contact, heterojunction, single-crystalline and multicrystalline structures. Therefore, it is very difficult to predict which technology is going to be viable in the future. But if we look at the recent trend, single-crystalline and back-contact silicon solar cells that have higher efficiencies will dominate the market.

Any comment on the market share in terms of deployed technology?
The total production of silicon solar cells is increasing rapidly. In 2002 the market share percentage was about 3%, and in 2009 it was 20%. In the future, it will be around 25–30%. In the next 20 years, crystalline silicon solar cells will dominate the market and the share of thin-film silicon solar cells will increase.

Interview by Rachel Won

Exhibition report

OPTO RESEARCH CORPORATION
Fast and precise spectroradiometer

OPTO Research Corporation showcased its pulse analysis spectroradiometer for measuring and evaluating the spectral distribution of pulsed light at both high speed and high precision. The unit, the OKL-HSSR1300, is ideal for verifying solar simulator compliance with IEC 60904-96 and Japanese Industrial Standards. The principle of pulsed light solar simulator emissions for production lines is to create an electrical discharge between poles on a lamp by emitting a charged electrical load to the capacitor. There is a resulting variation in emission timing of 10–100 μs, which makes performing accurate measurements problematic. To solve this problem, OPTO Research Corporation teamed up with AIST, Nisshinbo, Yamashita Denso and OK Labs to develop a trigger circuit required for high-speed synchronous measurements using the spectroradiometer. The spectroradiometer has dimensions of 340 mm × 300 mm × 280 mm and can measure wavelengths in the range of 350–1,300 nm with a wavelength resolution of 4 nm and an accuracy of ±1 nm.
www.optoresearch.co.jp

MITSUI CHEMICALS
Thermally stable transparent polyimide

Mitsui Chemicals is a provider of many photovoltaic materials, including encapsulants, backsheet adhesives and edge-seal materials with long-term reliability. The company showcased a thermally stable and transparent polyimide film that is still under development. Unlike poly(methyl methacrylate) and polycarbonate, which have high transparency but low thermal stability, and typical polyamides/polyimides, which have high thermal stability but low transparency, the polyimide film exhibited by Mitsui Chemicals offers both high transparency and high thermal stability, thanks to its proprietary design technology and monomer database. Three types of polyimide films are available: type A, B and C, which have glass transition temperatures of 290 °C, 260 °C and 280 °C, tensile moduli of 2.0 GPa, 2.8 GPa and 4.5 GPa, and tensile elongations of 8%, 18% and 15%, respectively. The total transparencies achieved are 90% for type A and B, and 87% for type C. The polyimide films produced by Mitsui Chemicals have relatively high and constant transparency over the entire visible range. For instance, the type A film has a transparency of 90% in the range of ~360–800 nm, whereas typical polyimide films have a slowly increasing transparency profile from 0% at ~460 nm to <80% at 800 nm.
http://jp.mitsuichem.com

SOLAR FRONTIER
Gigawatt-level production capacity

Established in the 1970s, Solar Frontier's mission is to create the world's most economical and ecological solar energy solutions. Its proprietary copper–indium–selenide (CIS)-based thin-film photovoltaic technology produces solar cells with high efficiency and low production costs, as well as superior reliability, stability, sustainability, nontoxicity and low overall energy consumption throughout the entire manufacturing process. Solar Frontier took the opportunity at the exhibition to announce its third photovoltaic production facility, which it claims to be the world's largest production plant. The facility, in Miyazaki, Japan, is scheduled to commence operation in 2011, and aims to bring the production capacity of Solar Frontier to the gigawatt level. In addition, the company also announced that it had recently achieved a record-high conversion efficiency of 16.29% in CIS-based thin-film photovoltaic solar submodules by optimizing the absorber thickness and circuit design.
www.solar-frontier.com/jp

SHARP
Thin-film solar module

With 50 years' development history in photovoltaics, Sharp continues to bring solar cells to practical use. One of the products exhibited by Sharp at the exhibition was its thin-film photovoltaic module, NA-HSL8G. Unlike normal crystalline silicon solar cells, which have a bulk silicon layer of ~0.2 mm, the silicon thin-film layer used in the NA-HSL8G is only around 0.002 mm. In addition, the cell is made in a tandem configuration that includes both an amorphous silicon layer and a thin film of silicon, based on Sharp's unique proprietary technology. The amorphous silicon layer absorbs visible light, whereas the silicon thin film absorbs infrared light. This tandem configuration extends the absorption range of the thin-film cell, hence increasing its overall conversion efficiency. The NA-HSL8G thin-film module measures 1,419 mm × 1,009 mm × 46 mm, and weighs 19 kg. It has a nominal maximum output power of 128 W at a voltage of 45.4 V and a current of 2.82 A.
www.sharp.co.jp/sunvista

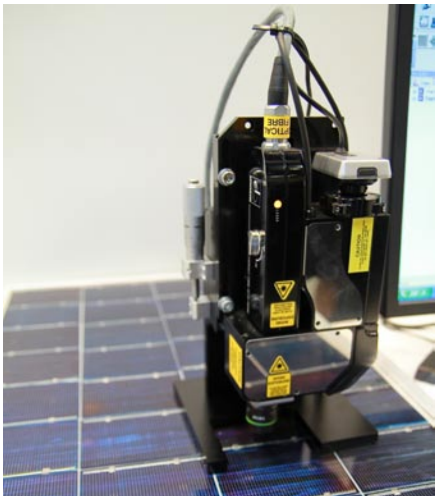
KYOSEMI
Three-dimensional light capture

Kyosemi demonstrated their light, durable and reusable micro-solar cell, Sphelar. Sphelar technology is based on tiny single-crystal silicon spheres measuring only 1–2 mm across. The spherical cells are interconnected with a thin filament, and the strings are lined up in a grid pattern and encased in either clear glass or a clear, flexible membrane that serves as the final product. Unlike flat, conventional solar cells, Sphelar allows light absorption from every direction, maximizing power generation without any tracking mechanism. It exhibits high pliability, allowing it to fit in various types of see-through, flexible or irregularly shaped modules. Because each cell is discrete, any combination of serial and/or parallel connections in a mesh-wiring scheme is available, overcoming partial shading problems. With the features of optical transparency, bifacial response and flexibility in layout, Sphelar allows for a wide range of innovative designs and applications that cannot be realized by flat cells.
www.kyosemi.co.jp

TRUMPF
Laser systems for solar modules

TRUMPF, one of the world's leading manufacturers of laser technology, has developed lasers that produce pulses of suitable duration and intensity for fabricating solar modules. One of these — the TruMicro Series — is most suitable for microprocessing, and is optimized for high speed and high accuracy. There are three TruMicro Series available — the 3000, 5000 and 7000. TruMicro Series 3000 enables selective and precise material ablation with high feed rates, and has lasers operating at wavelengths of 532 nm (TruMicro 3220) and 1,064 nm (TruMicro 3120) with maximum average powers of 12 W and 8 W, respectively. The powerful picosecond lasers of the TruMicro Series 5000 can vaporize most materials quickly enough to leave no heat-affected zone. Models operating at wavelengths of 343, 515 and 1,030 nm at different maximum average powers in the range of 5–50 W are available in this series. Thanks to the combination of short pulses and high average output, TruMicro Series 7000 offers rapid, large-area material ablation with ultrahigh throughput times. TruMicro 7050 operating at 1,030 nm has an output power of 750 W with a pulse duration of 30 ns, whereas TruMicro 7250 operates at 515 nm and has an output power of 400 W with a pulse duration of 300 ns. These lasers can help solar-cell manufacturers and facility builders to fulfil jobs such as patterning, edge deletion, edge insulating, removing, structuring, cutting, drilling and marking.
www.trumpf-laser.com

NISSHINBO MECHATRONICS
Non-destructive analysis



Nisshinbo Mechatronics creates materials and equipment to make photovoltaic modules with lifetimes of around 100 years. It analyses previous photovoltaic modules to reveal the relationship between lifetime and three production factors: materials, equipment and production recipe. It also works on inspection methods for module production and non-destructive photovoltaic module analysis technologies. At the exhibition, the company explained their concepts for next-generation materials and equipment that are based on their analysis.
www.nisshinbo.co.jp

UNDERWRITERS LABORATORIES JAPAN
Promoting product safety

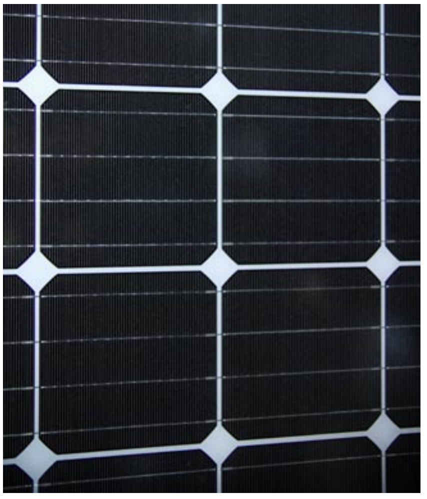
The mission of Underwriters Laboratories (UL) Japan is to contribute to society by promoting the safe product growth of renewable energy equipment as a power measure for coping with global warming. In September 2010 the company opened a photovoltaics laboratory in Ise, Japan, to complement its facilities in the USA, China and Germany, allowing it to serve customers at regions close to its manufacturing and deployment locations. Apart from providing performance and safety testing for photovoltaic equipment at its Japanese facility, UL Japan also provides technical support for Japan's photovoltaic equipment manufacturers when developing their businesses and entering overseas markets. At the exhibition, UL Japan presented its services for the photovoltaics industry under its global network, which includes product safety, field evaluation, verification services and global market access.
http://ul.com/jp

DKSH JAPAN
Market expansion service provider

Formerly known as Nihon SiberHegner, DKSH Japan is the Japanese branch of the Switzerland-based DKSH Group. Operating for more than 140 years in Japan, DKSH Japan is the country's leading provider of market expansion services, focusing on consumer and luxury goods, speciality chemicals, pharmaceuticals, food ingredients, and technology products and services. It

MITSUBISHI ELECTRIC CORPORATION
Monocrystalline module

Mitsubishi Electric Corporation showcased two photovoltaic modules — one for residential use, and the other for public/industrial use — together with a photovoltaic inverter for residential use. The company launched the photovoltaic module for residential use on 20 October 2010, during the conference. The module is based on monocrystalline silicon solar-cell technology, using lead-free solder for lower environmental impact, and incorporating photovoltaic cells with an efficiency of more than 5%. Four bus bars (instead of the standard two) are used to increase the output from each cell. The module comes in different shapes — rectangular (PV-MA2000B), square (PV-MA1000HB), right-trapezium (PV-MA1000RB) and left-trapezium (PV-MA1000LB) — accommodating rooftops with differently shaped areas. The rectangular-shaped panel contains 50 cells, producing an output power of 200 W, whereas the other models contain 25 cells, producing an output power of 100 W. The



large power output means that fewer modules are needed to build a system, helping to reduce the total system cost. The module costs ¥134,400, ¥72,765 and ¥79,380 yen for rectangular-, square- and trapezium-shaped panels, respectively. The company expects to sell 100,000 modules per year.
www.mitsubishielectric.co.jp

KYOCERA
High-efficiency multicrystalline module

Established on 1 April 1959, Kyocera have advanced their cell-processing technology and automated production facilities to produce a highly efficient multicrystalline photovoltaic module, the KD235GH-2PB. The unit is useful for grid-connected systems for residential, public and industrial use, as well as for standalone solar-power systems in microwave/radio repeater stations, villages and medical facilities in rural areas. Launched in July 2010, the KD235GH-2PB, measuring 1,662 mm × 990 mm × 46 mm, contains 60 squared multicrystalline silicon solar cells with efficiencies of >16%. The unit can produce a maximum power of 235 W. The cells are encapsulated between a tempered glass cover and a backsheet-covered pottant to provide protection from severe environmental conditions. The entire laminate is installed in an anodized aluminium frame to provide structural strength and ease of installation.

www.kyocera.co.jp

provides sourcing, marketing, distribution and sales, and after-sales services in many areas to help small and medium-sized companies grow their businesses in Japan. DKSH Japan introduced their range of services at the exhibition.

www.dksh.jp

DUPONT
Solutions for photovoltaic infrastructure

Dupont's vision is to be the world's most dynamic science company, creating sustainable solutions essential for improving the health, safety and quality of life for people around the world. Dupont offers a wide range of innovative products and services for markets such as agriculture, nutrition, electronics, communications, safety and protection, home and construction, transportation and apparel. Its broad and growing portfolio of solutions is key to the manufacturing of both crystalline silicon and thin-film solar cells. Dupont collaborates closely with other companies and institutions throughout the photovoltaic industry to help increase the power output per manufacturing dollar for photovoltaic technology, while also increasing the efficiency and lifetime of solar modules. The company introduced its advanced products and applications at the exhibition.

www.dupont.co.jp

MST
Analysing CIGS thin-film solar cells

The Foundation for Promotion of Material Science and Technology of Japan (MST) presented technical information regarding the structure and performance of copper–indium–gallium–selenide (CIGS) thin-film solar cells. Atomic-level characterization of local structures is important for realizing advanced high-efficiency CIGS solar cells. MST showed that high-angle annular dark-field scanning transmission electron microscopy is the most practical method for characterizing multicompound junction interface structures. The microscope provides direct visualization of atomic arrangements at atomic-level resolution. Another way to improve the characteristics of CIGS solar cells is to study the correlation between the microstructures and electrical properties of the absorber layer of the cell. By using scanning spread resistance microscopy and electron-beam-induced current, MST showed that the resistance and electrical potential distributions in the cell can be visualized, allowing the relationship between the microstructures and CIGS characteristics to be investigated.

www.mst.or.jp

AIST
Photovoltaics research centre

The Research Center for Photovoltaics, founded in 2004 by the National Institute of Advanced Industrial Science and Technology (AIST), is dedicated to performing comprehensive research into photovoltaics, from materials research to large-scale system design and characterization. Its primary goal is to develop the fundamental technologies required to decrease the cost of photovoltaic technologies to one seventh of their 2004 level by 2030. The centre comprises six teams, namely the Advanced Crystalline Silicon Team, the Novel Silicon Material Team, Thin Film Compound Semiconductor Team, the Characterization, Testing and System Team, the Advanced Organic Material Team and the Strategic Industrialization Team. AIST presented its recent results relating to the materials, processes, devices, modules and systems of various solar cells, including crystalline silicon, thin-film silicon, compound thin-film, dye-sensitized, organic film and quantum-dot solar cells. AIST also presented results from collaborative studies with private companies, including the Consortium Study on Fabrication and Characterization of Solar Cell Modules with Long Life and High Reliability, and the R&D on Innovative Solar Cells with NEDO.

http://unit.aist.go.jp/rcpv/ci

NEDO
Moulding a photovoltaic future

As Japan's public management organization promoting research and development while disseminating industrial, energy and environmental technologies, New Energy and Industrial Technology Development Organization (NEDO) aims not only to address global energy and environmental problems but also to enhance Japan's industrial competitiveness. NEDO presented the contributions it had made to the development of photovoltaic power generation technology, beginning with the New Sunshine Project in 1974, to the present day. NEDO also showcased a history of various photovoltaic mod-

SOMA OPTICS
Portable solar spectrometer

The portable and high-performance spectrometers showcased by Soma Optics — the S-2440, S-2441 and S-2442 — are especially designed for measuring sunlight and light from solar simulators. They are compact, with dimensions of 90 mm × 110 mm × 170 mm, and can perform wavelength measurements with a resolution of 5 nm in the range of 300–1,100 nm, covering the operational wavelengths of silicon, dye-sensitized and organic thin-film solar cells. Light detection is through the use of a cosine-type diffuse reflector. The response time is 2.5–1,000 ms for the S-2440 and S-2441 models, and 1–1,000 ms for the S-2442 model. The spectrometers can be easily operated using a computer running Windows XP/Vista/7, and are equipped with a USB 2.0 interface.

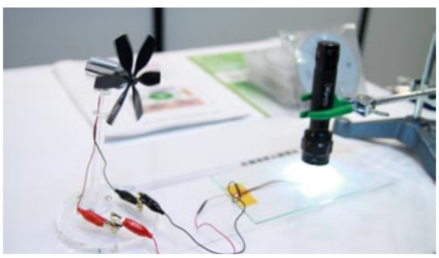
www.somaopt.co.jp

LINTEC
Durable backsheet

Lintec, a leading Japanese manufacturer of adhesives, exhibited LIPREA, a high-quality durable backsheet for photovoltaic module applications. Made using Lintec's proprietary vacuum heating and pressurizing processes, LIPREA's high durability is due to an outer coating of fluorocarbon. Two types of backsheet were exhibited at the exhibition: LIPREA-PKT and LIPREA-TFB. LIPREA-PKT is a multilayered laminate film suitable for long-term outdoor use. It has high reflectivity, providing high electricity generation, and a partial discharge of >1,000 V based on the IEC-60664-1 standard. IPREA-TFB has a high water resistance of <0.005 g m^{-2} per day — lower than LIPREA-PKT's value of 2 g m^{-2} per day — owing to the additional layer of aluminium foil placed underneath the fluorocarbon coating. LIPREA-TFB is especially suitable for use in thin-film photovoltaic modules. In both types, backsheets with white-coloured surface demonstrate high reflectivity, providing high electricity generation. LIPREA offers the necessary functions required for high-performance photovoltaic modules, such as high durability, a good moisture barrier, electrical insulation, dielectric properties and outstanding adhesion to encapsulants.
www.lintec.co.jp

ules, showing the evolution of photovoltaic technologies such as monocrystalline, multicrystalline, amorphous thin-film, compound thin-film, CIS, III–V, dye-sensitized and organic thin-film solar cells and modules. With the aim of accomplishing power generation costs of 7 yen kW^{-1} h^{-1} by 2030, NEDO introduced "a photovoltaic power generation roadmap" (PV2030+), which shows the direction in which photovoltaic technology development must progress.
www.nedo.go.jp

JST
Realizing a low-carbon society



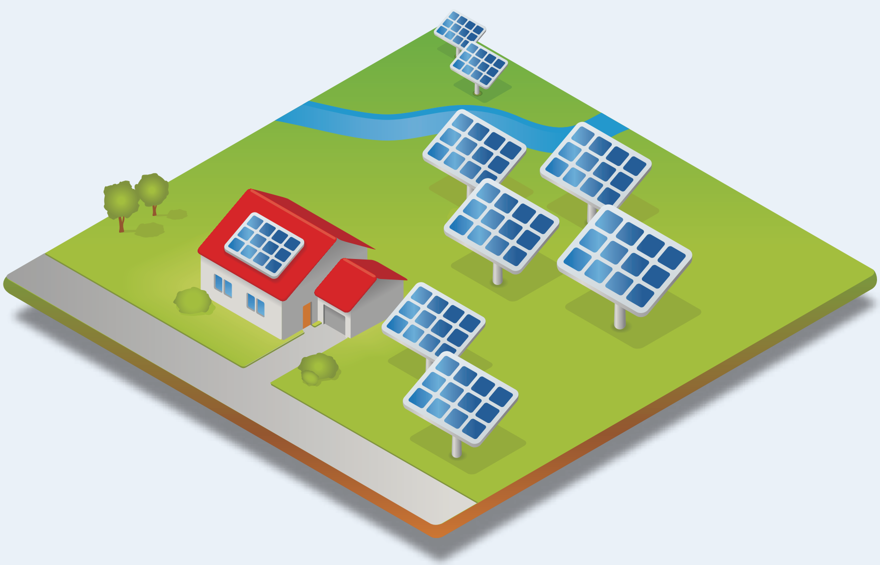
The Low Carbon Society is a research centre established by the Japanese Science and Technology Agency (JST) to develop strategies and scenario proposals for realizing a low-carbon society. Its research aims to address several key factors in the development of low-carbon technologies — photovoltaics, for example — by looking at the progress needed for their widespread diffusion. JST presented the overall challenges faced by the Low Carbon Society and explained its new funding project in 2010 — the Advanced Low Carbon Technology Research and Development Program — which will contribute to developments in low-carbon technology. JST also presented some of the latest achievements made in its Basic Research Program, such as prototype samples of organic thin-film photovoltaics, microbial solar cells and polymer/low-molecular hybrid cells.
www.jst.go.jp/alca

THE UNIVERSITY OF TOKYO
SolarQuest

As the only university-based research institute at the exhibition, the Research Center for Advanced Science and Technology of the University of Tokyo introduced SolarQuest, an international research centre for energy and environmental technology designed to tackle global environmental problems. SolarQuest pursues comprehensive activities related to energy and environmental technologies through research and development, development strategy and diffusion strategy. Its emphasis is on partnerships among universities, companies and governments, both inside and outside of Japan. Currently, its main subject of research is solar power generation, in which it aims to improve the efficiencies of optical-to-electrical energy conversion and solar power generation systems, as well as the performance of light concentrators, silicon-refining technologies and new cooling systems. SolarQuest presented "Post-silicon solar cells for ultra-high efficiencies", an innovative research and development project supported by NEDO and the Ministry of Economy, Trade and Industry, which aims to achieve conversion efficiencies of more than 40% by exploring novel concepts such as concentrator multijunction solar cells, quantum structure tandem solar cells and hybrid-materials solar cells, as well as through non-silicon-based approaches such as dye-sensitized, organic and III–V-based solar cells.
www.rcast.u-tokyo.ac.jp/en

NIHON ENTEGRIS
Easing the phototransformation process

Nihon Entegris focuses on improving the phototransformation efficiency of solar cells while also reducing manufacturing costs. The company showcased its filtration/purification products and new shipping containers at the exhibition, emphasizing its two key technologies of contamination control and plastic moulding. Contamination control technology is for the filtration and purification of chemicals in different gases and environments. Entegris introduced a diffuser filter required in the vent chamber for processes involving environmental transformation from the vacuum to the atmosphere. The diffuser filter is needed to ensure that laminar flow — instead of turbulent flow, which stirs all particles in the chamber — keeps all particles at the bottom of the chamber. Entegris's plastic moulding technology is for the shipping, storage and process transport of wafers and cells. Its main function is to reduce breakages during shipping, as well as to reduce the time needed for taking wafers and cells in and out of shipping containers.
www.entegris.com



Future perspectives on photovoltaics