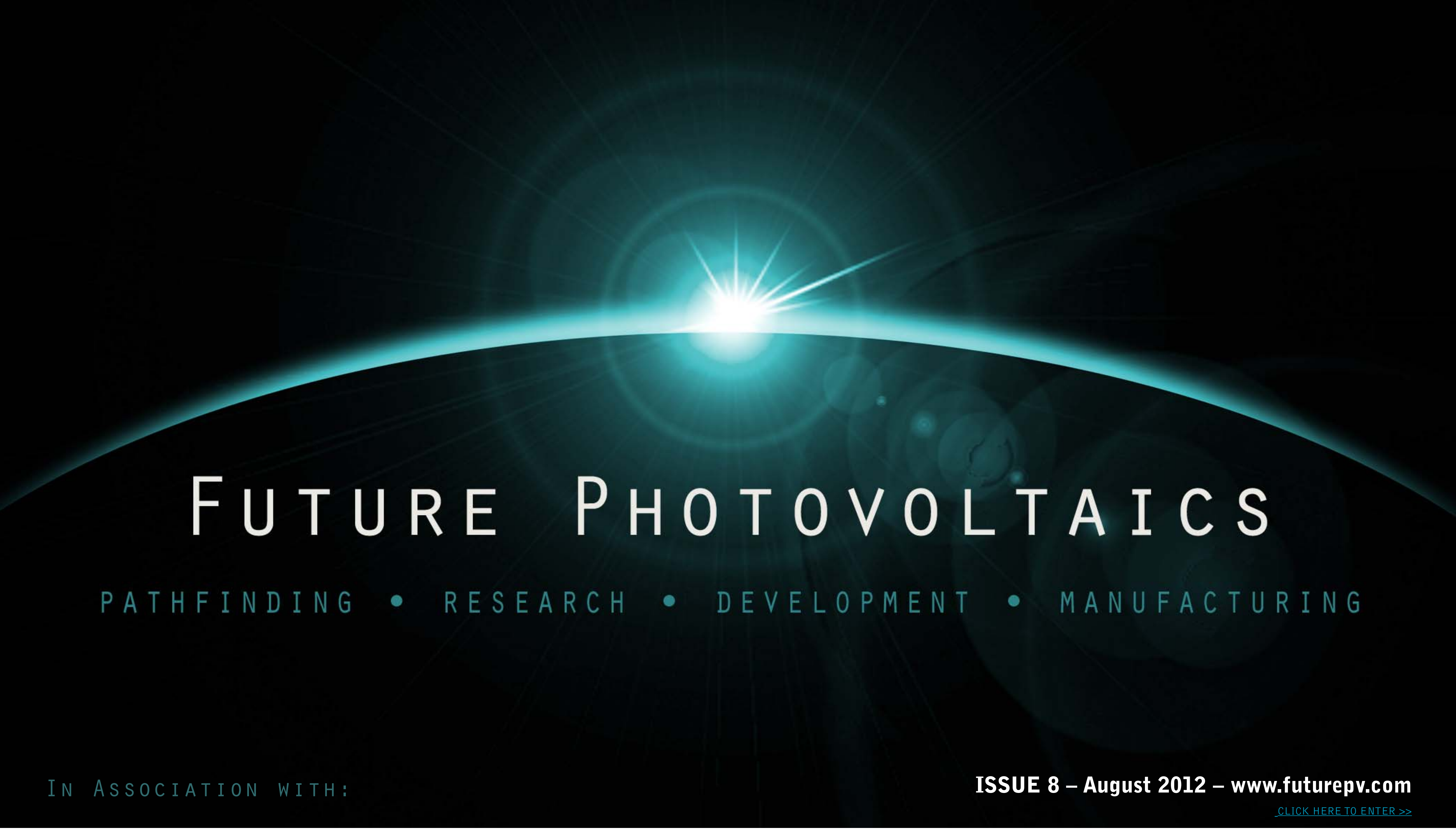

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"Presently, the majority of photovoltaic devices are Si based..." Wieteke D.A.M. de Boer et al. - p29

Welcome to the latest issue of Future Photovoltaics ...

As the photovoltaic industry collectively licks its wounds from a very painful 2012, it can be hard to be optimistic about times like these. However, history teaches us that all technology industries have cycles, and all this proves is that PV is not immune to cycles. With the thinning out of the field, the hope is that those who survive will become stronger and more competitive. This type of climate also allows new players entry into previously crowded marketplaces, and as we at Future PV do like to focus on the future, we remain optimistic about the new technologies that are coming close to mainstream – watch this space.

In the meantime, we hope you enjoy this issue!
The Future PV Team

FUTURE VISIONS & CURRENT CONCERNS

NEW TECHNOLOGIES & MATERIALS

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METROLOGY & FAILURE ANALYSIS

MODULE & PANEL, TEST & CONSTRUCTION

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EDITORIAL PANEL

For the full versions of the following biographies, please click here

Welcome to our new Panel Members

Armin Aberle

CEO, Solar Energy Research Institute of Singapore (SERIS),
National University of Singapore

Prof. Aberle's research focuses on reducing the cost of electricity generated with silicon solar cells. In the 1990s, he established the Silicon PV department at ISFH in Germany. Prof. Aberle then worked for 10 years in Australia, as a professor for PV at the University of New South Wales. In 2008, he joined NUS to establish SERIS, with particular responsibility for the creation of a Silicon PV department.

Ernst Richter

Liaison Officer/Senior Manager

Ernst Richter is liaison officer and senior manager at Avancis, a Saint-Gobain subsidiary, with broad international experience in the PV and IC industries. His professional employment started at Siemens. Dr. Richter holds a Ph.D. and an M.Sc. in chemistry and an M.Sc. in material science.

Urs Schoop

Chief Technology Officer, Global Solar Energy

Urs Schoop is chief technology officer at Global Solar Energy. Prior to joining Global Solar, he was a senior scientist with American Superconductor in Devens, Massachusetts. Dr. Schoop earned his Ph.D. in applied physics from the University of Cologne, Germany, in 2000.

Robert Birkmire

Director, Institute of Energy Conversion;
Professor of Materials Science, Professor of Physics

Robert Birkmire is director of the Institute of Energy Conversion, a U.S. Department of Energy Center of Excellence for Photovoltaic Research and Education, as well as professor of materials science and engineering with a secondary appointment as professor of physics. He is author of over 150 technical publications and is inventor on eight U.S. patents.

Richard Bozicevich

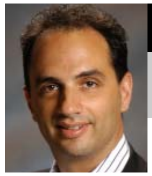
Vice President of Business Development;
TUV Rheinland Photovoltaic Testing Laboratory - PTL

Mr. Bozicevich is the VP of Business Development for TUV Rheinland Photovoltaic Testing Laboratory, a division of TUV Rheinland Group. He is responsible for the market development of photovoltaic testing services in the North and South American Markets. Richard received a B.S. in electrical engineering from Michigan Technological University, and currently sits on a number of commercial and technology advisory boards for solar technology implementation.

Alain C. Diebold

Empire Innovation Professor of Nanoscale Science, College of Nanoscale Science and Engineering, University at Albany; AVS Fellow; Senior Member of IEEE

Alain's research focuses on the impact of nanoscale dimensions on the physical properties of materials. He also works in the area of nanoelectronics metrology. Alain is a member of the International Metrology Technical Working Group, founder and co-chair of the U.S. Metrology Technical Working Group for the 2007 International Technology Roadmap for Semiconductors, and chair of the manufacturing Science and Technology Group for the American Vacuum Society.



Bryan Ekus

Managing Director, International Photovoltaic Equipment Association

Bryan Ekus is the managing director of the International PV Equipment Association (IPVEA). In this role, he is responsible for overseeing the associations operations and strategic position in the PV industry. Bryan is also the managing director of the MEDIA-TECH Association that serves the packaged media industry. He has over 25 years experience working internationally and currently resides in Orlando, Florida.

Robert E. Geer

Professor, Nanoscale Science; Vice President, Academic Affairs
College of Nanoscale Science and Engineering; University at Albany

Robert E. Geer is a professor of Nanoscale Science and vice president for Academic Affairs in the CNSE at the University at Albany. His research in emerging energy applications, nanoelectronics and nanomaterials has been supported by the National Science Foundation, the Office of Naval Research, the Department of Energy, the Air Force Office of Scientific Research, the Semiconductor Research Corporation, DARPA, International SEMATECH and the New York office of Science, Technology and Academic Research.

Oliver Mayer

Principal Scientist for Solar Systems; Head of Quality at GE Global Research, Munich

Oliver Mayer is a principal scientist at GE Global Research in Munich, responsible for solar system technologies and energy concepts for complex systems such as cities or hospitals, etc. For more than 20 years he has worked in the field of solar systems, having gained field experience by installing PV systems in such countries as Jordan, Eritrea, Uganda, Chile and Germany. Oliver received his Ph.D. from UniBwM, and is an honorary professor for solar systems at the Munich University of Applied Science.

Christoph J. Brabec

i-MEET Chair, Friedrich Alexander University Erlangen-Nürnberg

Christoph holds the chair "materials for electronics and energy technology (i-MEET)" at the materials science department of the Friedrich Alexander University Erlangen-Nürnberg. He is also the scientific director of the Erlangen division of the Bavarian research institute for renewable energy (ZAE Bayern, Erlangen). He received his Ph.D. (1995) in physical chemistry from Linz University.

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EDITORIAL PANEL

For the full versions of the following biographies, please click here

Torsten Brammer

Torsten Brammer, Consultant, Photovoltaic Research and Consulting

Torsten Brammer has focused on photovoltaics since 1993. At the Research Center Jülich (Germany), he did his dissertation on thin film PV. Since 2011, he has been offering consulting services for technology, product design and business planning.

Hansjörg Lerchenmüller

Co-Founder of Concentrix Solar, now a division of Soitec

Hansjörg Lerchenmüller is the co-founder of Concentrix Solar, now a division of Soitec. He holds a degree in physics from the University of Karlsruhe. Before. Lerchenmüller became CEO of the Fraunhofer spin-off Concentrix Solar, he worked for 10 years at the Fraunhofer Institute for Solar Energy Systems ISE in Freubyrg.

Dean Levi

Principal Scientist
National Center for Photovoltaics; National Renewable Energy Laboratory

Dean Levi is currently a line manager and senior technical staff member in the National Center for Photovoltaics at the National Renewable Energy Laboratory. He received his Ph.D. in physics from the University of Illinois at Urbana-Champaign in 1990.

Philippe Malbranche

Research Programme Manager, CEA-INES

Philippe Malbranche is the research programme manager at CEA-INE. He received his engineering degree at the Ecole Centrale de Paris. He is also a member of the Steering Committee of the European Photovoltaic Technology Platform.

J. Michael Walls

Professor of Photovoltaics, Centre for Renewable Energy Systems and Technology (CREST), School of Electrical, Electronic and Systems Engineering, Loughborough University, U.K.

Michael Walls is responsible for PV device research within CREST at Loughborough University; his research focus is in thin film CdTe PV. He is an active member of the Institute of Physics in London and the organizer of the annual “Advances in Photovoltaics” meeting. Dr. Walls has authored over 120 papers, three books and is the inventor of 17 patents.

Danielle Merfeld

Director, Solar Technology Platform; GE’s Global Research Center

Danielle Merfeld is the director of the Solar Technology Platform at GE’s Global Research Center. She is responsible for managing the PV-related projects across the Center. Danielle received her B.S. in electrical engineering from the University of Notre Dame, and her Ph.D. in electrical engineering from Northwestern University. She has authored or co-authored over 60 papers in refereed technical journals.

Craig Hunter

Senior Vice President & General Manager
Clean Energy Group, Intermolecular

Craig Hunter runs Intermolecular’s Clean Energy Technologies Group. Some of Mr. Hunter’s previous roles include: senior manager for the E-beam Test (EBT) and PVD Products of AKT, Inc.; CFO of Evercare Corp.; and director of M&A at The Beacon Group. He received a B.A. in East Asian Studies from Harvard College and graduated with high distinction from Harvard Business School.

Eelco Bergman

VP of Business Development; Cyrium Technologies Inc.

Eelco is VP of Business Development with Cyrium Technologies, Inc. Prior to Cyrium, he was a founding member of V-CAPS and spent 14 years with Amkor Technology. Previously, Eelco spent four years in the Netherlands managing manufacturing operations for Eurasem, BV and held a variety of engineering management positions with Micron Technology, Inc. He has a B.S. in aerospace engineering from the University of Michigan.

Brent Nelson

Group Manager, Process Development & Integration Lab;
National Renewable Energy Laboratory

Brent Nelson is PDIL group manager for the NREL, where he oversees a laboratory designed to integrate as many of the PV technologies and material characterization techniques as possible. He has authored 18 publications as well as co-authored an additional 77 other scientific publications. Brent holds a B.S. in engineering physics from the Colorado School of Mines.

Kristian Peter

CEO, ISC Konstanz

Dr. Peter is a co-founder of ISC Konstanz and a member of the board of directors, as its CEO. Since January 2007, he has been working full time as a researcher, leading the department of advanced solar cell processes. Kristian obtained his M.S. in physics in 1993 at the University of Konstanz, and his Ph.D. in applied solid state physics in 1997.

Jef Poortmans

Department Director Solar and Organic Technologies, imec

Jozef Poortmans is program director of the Strategic Program SOLAR+ at imec. He has authored or co-authored nearly 350 papers that have been published in conference proceedings and technical journals. Jef is a board member of the EUREC agency and was general chairman of the 21st European Photovoltaic Solar Energy Conference & Exhibition. He received his Ph.D. in 1993 on strained SiGe-layers.

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EDITORIAL PANEL

For the full versions of the following biographies, please click here

Steve Roberts

Automation Engineer, Heliovolt Corporation

Currently an automation engineer with Heliovolt Corporation, Steve recommends and implements SCADA, MES, SPC, automated material handling and equipment control systems for thin films photovoltaic panel manufacturing. For more than 20 years, he has been a software/control systems product manager and engineer in the semiconductor and electronics manufacturing industry.

Stefan Glunz

Director, Division of Solar Cells – Development & Characterization; Fraunhofer ISE

Stefan W. Glunz directs the Division of Solar Cells – Development and Characterization at Fraunhofer ISE. He also teaches and lectures at the University of Freiburg. Dr. Glunz received his Diploma and Ph.D. (Dr. rer. nat.) in physics from the Albert-Ludwigs University in Freiburg. He has authored/coauthored over 80 journal and 250 conference papers and is the founding editor of IEEE Journal of Photovoltaics.

Jörg Müller

Director
R&D Cells, Q-Cells SE

Jörg Müller is director of R&D Cells at Q-Cells SE, one of the leading worldwide PV companies with a strong technology focus. In this role, he is responsible for the development of the crystalline silicon solar cell technology. Jörg holds a master’s degree in physics from the University of Munich and a Ph.D. from the University of Hannover.

Rommel Noufi

Principal Scientist, National Renewable Energy Laboratory

Rommel Noufi is a principal scientist with the National Renewable Energy Laboratory in Golden, Colorado. He is also a visiting professor at Stanford University. Rommel received his Ph.D. in analytical/physical chemistry from the University of Texas. He has published more than 170 papers and has been issued eight NREL patents.

William Richardson

Head of Research & Development, SOLON Corporation

William Richardson heads Research & Development for SOLON Corporation, where he oversees module testing and product development as well as strategic management and evaluation of new technologies for the North American market. Bill holds dual degrees in Renewable Natural Resources and Electrical Engineering from the University of Arizona, where he currently sits on the advisory board for the Material Sciences and Engineering Department.

Wim C. Sinke

Program Development Manager
ECN Solar Energy, the Netherlands

Prof. dr. Wim C. Sinke is program development manager in the Solar Energy unit of the Energy Research Centre of the Netherlands (ECN). He is an active member of the European Photovoltaic Technology Platform. In 1999, he received the Royal Dutch/Shell Prize for Sustainability and Energy for his work in the field of photovoltaic solar energy.

Robert David Vinje

VP of Expansions, SunPower Corporation

Robert Vinje is VP of Expansions for SunPower Corporation. He resides on the Board of Trustees of Investors for First Philippines Industrial Park, and chairs the Malaysian Alternative and Renewable Industry committee in Malaysia. Vinje has an electronics degree, an electrical engineering degree and an MS degree in management of technology from the University of Minnesota.

Lior Handelsman

VP Product Strategy & Business Development, Founder; SolarEdge Technologies

Lior Handelsman is responsible for the company's product management and business development activities. Mr. Handelsman holds a B.Sc. in electrical engineering (cum laude) and an MBA from the Technion, Israel Institute of Technology in Haifa.

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Robert E. Geer
Professor, Nanoscale Science; Vice President, Academic Affairs
College of Nanoscale Science and Engineering; University at Albany

Is the global PV industry mature? Most insiders would say no. But none would argue that it is indeed maturing; and by most measures, that maturation is accelerating.

In this section, we are treated to two complementary viewpoints on technology maturation, and PV maturation in particular. Pierre Verlinden, chief scientist and vice chair of the State Key Laboratory of Photovoltaic Science and Technology, Trina Solar, China, argues that PV has turned the corner of adolescence and lays out what it will take for PV to make a run at adulthood. From a more general perspective, Linda Steele Wilson, program manager for the International Technology Roadmap for Semiconductors (ITRS) and the U.S. CIGS PV Roadmap, looks at the evolution of technology roadmapping and highlights key elements of its success – lessons the PV industry should heed.

Both of these commentaries are particularly salient. Verlinden notes that conversion efficiency does not drive PV system technology as it did in PV's infancy. System considerations such as reliability, overall energy production rate, and competitiveness in the levelized cost of electricity (LCOE) are dominating PV maturation as subsidized manufacturing is replaced by true grid parity. In other words, innovation driven by large-scale volume manufacturing and overall system performance as measured by LCOE is the path forward.

But if PV manufacturing skills and system-level innovation are replacing the technical fixation on simple conversion efficiency, how do we chart this path? Wilson draws from her vast ITRS experience to lay out a plan for effective, industrywide roadmapping. She argues for strong pre-competitive engagement across an industry ecosystem and highlights the most essential components for a technology roadmap to maintain its relevance. On its own, Wilson's analysis of successful roadmapping is great reading. Combined with Verlinden's view of PV maturation, it's clear we should be looking at the path of the PV industry in a new light.

Roadmapping Considerations

Linda Steele Wilson
SEMATECH

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Roadmapping is usually described as an effort to address pre-competitive issues, but the term "pre-competitive" is not so easily defined: Manufacturing and technology challenges that are common to many organizations can be defined as pre-competitive by some but areas of competitive advantage by others. A more accurate definition is that roadmapping is an effort to indicate difficult challenges and imminent areas of need, and to project where competitive opportunities may arise as the industry and research community seek solutions in the competitive space.

As we approach the 20th anniversary of the semiconductor industry roadmap, this collaborative model is still considered one of the most valuable tools for industrial technology management. As part of this extraordinary activity for 19 of those 20 years, I have witnessed the evolution of this effort, and have a few observations about roadmapping I feel are worth sharing.

The early process of the semiconductor roadmap yielded many lessons learned as the effort staked out new territory in collaborative work. The process was intensely scrutinized by chipmakers, suppliers and researchers. While the first semiconductor roadmap was initially presented as a final report, it was immediately determined that more work and some correction was needed. This resulted in another edition and a change in the process to include routine revisions. Criticisms of the new roadmap led its leadership to mandate the inclusion of all industry representatives from across the supply chain and to issue an open invitation to participate in the working group teams and public forums, as well as to undertake a careful examination of the information and roadmap goals for the industry. Above all, producing a credible set of projected data – backed by empirical data as well as cited works – that was consistent throughout the various technology chapters was requested of and met by the working group teams. The subsequent roadmap reports eventually achieved high credibility through good guidance and careful vetting throughout the process.

Over time as the controversial effort called "roadmapping" proved valuable to the chipmaking industry and its supplier and research communities, other industries took note of the value of this type of collaborative effort. Indeed, the semiconductor industry roadmap is the "gold standard" for industry mapping. It has been used as an example and model for many industries and organizations and is currently part of the curriculum in several business schools. The term "roadmap" now commonly indicates a long-term plan or assessment in the typical business lexicon.

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As more industries use this approach to project their manufacturing or technology needs, numerous roadmapping success factors have emerged. These include having contributors as team members that represent the entire industry base (e.g., either manufacturing supply chain or technology systems); corporate support for the effort; and a centralized, neutral communications infrastructure for ease of information sharing. Additional but lesser-known elements of roadmapping that are critical to maintaining its credibility and relevance include industry analysis and cost modeling; understanding of the phases of roadmap maturation; and awareness of roadmap use through solid demographic data.

First let's look at the more common success factors of inclusive membership, corporate support and a neutral, centralized information hub …

Having all sectors of the industry engaged in the effort is critical. For example, including representatives from the entire supply chain as well as from the research community ensures a comprehensive assessment of future needs, from the perspectives of research, development and manufacturing. The synergy of all groups engaged in the process uncovers dependencies among the various industry sectors, and the consistency of the data and the careful reviews by a variety of experts provide a solid vetting. By considering a host of variables such as processing and product attributes from from various perspectives, a roadmap is more credible and more likely to contain valuable insights and guidance on manufacturing solutions and areas for technology innovations.

Corporate support and sponsorship of the roadmapping effort allows the teams that serve as working group members – mostly volunteers that take on the activity in addition to their assigned job tasks – the necessary freedom to be thorough and thoughtful. When their roadmapping activity is seen as complementary to their "real" job activities, their expertise helps feed the roadmap knowledge base for their working group and contributes to pre-competitive assessments. Likewise, they and their companies garner valuable information from partaking in roadmap sessions with others who have similar expertise and job histories, and they learn first-hand the latest information resulting from the roadmap sessions, well before the roadmap reports are released at the end of each year. This is one of the value propositions of roadmapping – "firsthand" knowledge of the latest roadmap information.

Another well-known success factor is a neutral and centralized infrastructure for communications and information sharing. Impartial management of roadmap communications reinforces the "pre-competitive" position required in industry roadmapping. Unbiased editorial and publication support maintains continuity and consistency for those involved in the roadmapping effort as well as assistance and contact support for the roadmap users. For this reason, nonprofit organizations or consortia are uniquely positioned to manage roadmap communications and information.

In addition to these more commonly known attributes for successful roadmapping, several other components are critical to a roadmap's relevance and usefulness to industry and research. These attributes include current knowledge of the industry's health and economics, roadmap process evolution, and roadmap demographics. They are crucial to a solid roadmap, as they help maintain the roadmap as a current set of information capable of evolving as its respective industry matures.

1. While technology working groups are a major component of any roadmap initiative, a central team for defining overall roadmap characteristics and metrics is the cost modeling and industry analysis group. The value provided by an industry analytical team is the collection and presentation of data from respected sources as the unbiased view of the current industry indicators and the governing trends for that industry's economy. These data are the basis of the roadmap metrics that the working groups use to grade future trends. The roadmap industry analysis team lays this critical foundation. As such, the industry analysis team and cost modelers are the first "cartographers" of the effort. They develop the first maps that detail industry historical trends and indicators and offer assumptions for roadmap manufacturing or technology trends. These teams present the current map for the working groups to measure against. While all the teams determine the set of roadmap drivers or metrics, and help determine where to go next, industry analysis sets the reference points.

   Additionally, cost modeling identifies the assumptions, variations and permutations associated with all aspects of manufacturing and product attributes in a consolidation of models that are useful to the entire industry, not just those who use the models internal to their own companies. Having connections between a cost model team and a roadmapping effort creates a feedback loop that provides a critical "sanity check" while assessing technology values, realistic innovation projections and potential solutions. This feedback loop provides a set of the best economic tools and knowledge to those who will ultimately guide the industry at large using the roadmaps. This team then provides a constant "system check" of overall industry characteristics.

2. Understanding the life cycle of a roadmap and enabling its evolution are essential to its development and progression. Roadmapping should be perceived from the onset as a dynamic and evolving process, with achievable expectations that match the effort's maturity. A new roadmap initiative has activities that differ significantly from a mature roadmap program. Team members that participate in the new effort must understand that there is a "startup phase" of establishing goals, building teams, identifying overall drivers and assembling good project management practices that are clearly communicated to produce a timely outcome for the user community. Working through these steps methodically, while also trying to "build a roadmap," is challenging, as the attention to management details can encumber the development of actual content unless the teams have

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clear instruction and leadership through the early part of the process. These instructions include the level of detail and correct focus.

A new roadmap has information useful to the industry with the right level of detail for manufacturing or technology assessments of current as well as potential challenges and needs. The data must be factual and provable, and consistent throughout the roadmap. With the challenges of starting a developing roadmap, the first roadmap reports should have a more narrow and high-level focus until the activity is established. It is achievable then to be clearly focused with solid information that is concentrated and vetted in a few areas of need.

The next phase of maturation involves review and improvement with the inclusion of more detail and, in many cases, correction and adjustment, since the foundation work has been accomplished with earlier versions. As roadmaps mature, they typically become broader in scope and detail. The working groups mature as teams, too, and become more efficient in their assessments. Feedback from users, as well as industry reaction as the roadmap is implemented, also affects the information contained in the reports.

Having this knowledge of how a roadmap evolves and advances over time with seasoned teams is important in the beginning phase of the roadmap. Communicating expectations about the end result of a "first pass" and vision of an early roadmap with the ultimate goal of subsequent roadmap work improves a roadmap's chance of success because all involved are working toward the same goal.

3. Collecting demographic information abouot participants, users and reports substantiates a roadmap's importance and relevance and provides metrics on roadmap information use. Team membership information, such as company representation and industry sector involvement, indicates who is participating in the effort as well as the gaps in participation. Targeted recruitment of potential new members to fill these gaps ensures the roadmap participation remains inclusive. Roadmap information use data that can be collected while respecting personal privacy through general IP monitoring such as unique visits to Web pages and suffixes that indicate location such as city, country and type of organization (e.g., corporate, educational or governmental). Additional analysis may include counting the number of individual file downloads to show which reports are of greatest interest. These details of roadmap users and report interest data indicate what information is popular among the users and what information may have more of a niche interest. This information can then be used to continue improving the roadmap.

Many of us involved in roadmapping have seen its evolution and maturation, and participated in roadmap initiatives with a variety of success. I have had the good fortune to work on a successful roadmap effort – complete with the challenges of growing pains and subsequent lessons learned – and to work with talented individuals who contribute to its success with good leadership and steady, committed working group participation. Ultimately, the people who volunteer for this effort and believe that such collaboration can work, proactively address criticisms and strive for continual improvement are the most important success factor of all. ■

About the Author

Linda Steele Wilson *is the program manager for the International Technology Roadmap for Semiconductors (ITRS) and the U.S. CIGS PV Roadmap. Before joining International SEMATECH, she attained a broad background in the semiconductor industry assignments in manufacturing operations, process engineering and R&D, and research consortium activities, with a focus on failure analysis in chip test and packaging. She graduated from St. Edwards University.*

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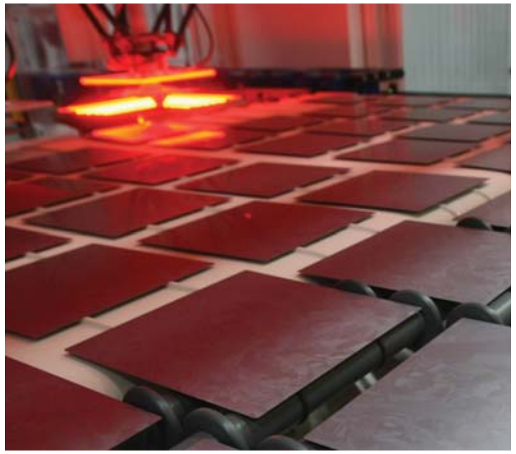
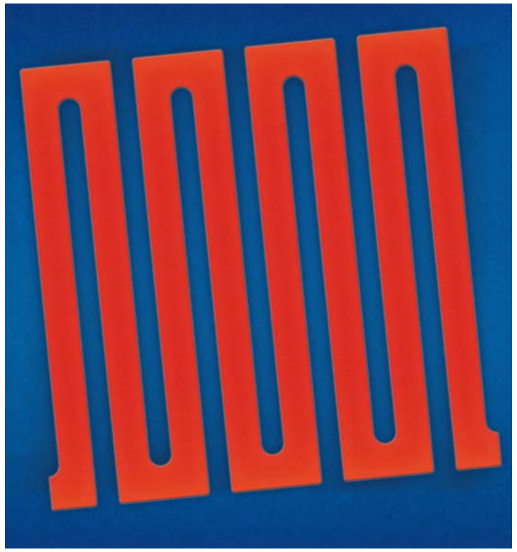
High-Temperature Materials: Performance and Purity

The photovoltaic industry roadmaps point to increased complexity of cell processing to enable improved cell efficiencies while decreasing the final cost to customers. Many of these processes occur at elevated temperatures or in applications where the materials used in the process equipment require special properties of electrical or thermal conductivity.

There are many applications in both silicon and thin film manufacturing where it is necessary to have a uniform heating source, either for preheating a surface before a deposition step or for curing of a previously deposited material. Graphite is a material of choice for many heater applications due to its beneficial electrical and thermal properties. Graphite being composed solely of carbon eliminates the opportunity for metal contamination that occurs with the use of metallic heater elements. There are a wide variety of graphite materials available on the market and not all are suitable for heater applications in the photovoltaic market. Entegris provides specific grades of graphite that meet photovoltaic application requirements. In particular, for applications greater than 300 °C, impurities in the graphite will become volatile and a source for potential metallic contamination. Entegris offers best-in-class graphite purity to minimize contamination. Additionally, the microstructure of the graphite impacts the performance of the product when used as a heater element. Non-uniform microstructures can lead to non-uniform temperature distribution in the heater elements, which is then propagated to the substrate. Non-uniform microstructures can also be sources of hot spots that can lead to premature failure of the heater elements, resulting in unpredictable and increased downtime of equipment. Entegris POCO® graphites have the most uniform grain structure in the industry to maximize both process performance and component lifetime.





In addition to graphite, Entegris offers other high-purity materials including silicon carbide that are used in demanding high-temperature processes. The roadmap ahead is challenging as the industry stretches to achieve new heights in technology and commercial adoption. Entegris is working along with equipment OEMs and cell manufacturers to meet the future stringent demands.

Offering a broad portfolio of proven fluid management, high-performance materials and substrate handling solutions, Entegris solves the contamination, repeatability and process efficiency challenges faced in your manufacturing environment. With 17 laboratories and 2,700 employees worldwide, Entegris serves you with global service and applications support teams.

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The Surviving PV Companies

Pierre Verlinden
Trina Solar

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Abstract

The great price decline of PV modules is pretty much over. With almost zero gross margin, PV companies are struggling to stay alive. The PV industry will finally be mature when it can stand on its own two feet without subsidies. The companies that will survive must offer highly reliable products, have impeccable manufacturing skills and demonstrate innovation to reduce LCOE.

Looking in the rearview mirror, sometimes I cannot help but think that PV is a slow riser. People who are new to the PV business, and who have experienced a very exciting industry since the mid-90s, may think that we are now a mature industry, entering a classic cyclical pattern and experiencing the first stumbling block. In fact, PV has had quite a rocky road so far, and the old-timers are here to testify to the long list of failed technologies, defunct startups or well-established PV companies that went through numerous ups and downs, often changing names and ownership along the way.

First, we had about 40 years of gestation, making the first PV devices, then the first PV modules and the first PV systems, and thinking that the future of PV was in space or in the developing countries. We all thought that PV was the best value proposition for areas where the grid had not extended its tentacles. We saw a great future for PV in Africa and Asia, pumping water and powering villages without connection to the grid. The humanitarian aspect of PV was an integral part of the roadmap, at least in the PV R&D community.

It was only in the late '80s that a few PV entrepreneurs thought that PV could have a future in developed countries, on the roofs of those baby boomers with significant disposable income and an unsatiated desire for renewable energy. Suddenly the PV value proposition became "to have the freedom to choose where my electricity comes from." That is actually when PV was born, and not, as most people would say, with its "conception" in the Bell Labs in 1954. I would place the birth of PV around 1996, when one saw a significant change in the annual growth of the world PV market. The German FIT (feed-in tariff) was established. PV was able to establish its presence in developed countries, benefiting from generous incentives, first in Japan, then in Germany, followed by Spain, etc.; the humanitarian objectives forgotten along the way. That is what I would call the infancy of PV, characterized by fast growth, recklessness and insouciance.

The adolescence of PV started about 12 years later, in 2008, with the global financial crisis, the reduction of FIT or even its cancellation, with retroactive effect in some countries. The adolescence of PV is characterized with troubled times and with struggling PV manufacturers, developers and installers. It is also characterized by overcapacity in manufacturing and unrealistically low sales prices. Some people may point their fingers at each other, but the main reason for this troubled adolescence of the PV industry was the incapacity of governments to establish reasonable incentives for PV and to ensure a smooth transition toward an incentive-less market. The "stop-and-go-and-stop again" character of the government incentives is the cause for the instability that we experience now.

The companies with better gross margin and those who had a more "adult" way of managing their cash flow are the current winners. How long will this adolescence period of PV last? It seems that it will last as long as PV cannot stand on its own two feet. It will depend on many factors, including the increasing cost of conventional fossil energy and how fast the PV market can grow over the next few years, i.e., how fast the PV industry can go down the experience curve. Many experts have predicted that these troubled times will last only a couple of years. I predict that maturity and the adult life of PV will start after 2015, maybe around 2018, when PV can be considered a mainstream technology for bulk electricity production, on the same level as gas, coal, wind or nuclear. In the meantime, unpredictable incentives will continue to drive the PV industry crazy.

We are at the point where the gross margin of most PV companies has almost completely vanished. While the cost of manufacturing PV modules has decreased tremendously over the last few years, it has been compressed to the minimum possible with the current PV technologies and volume of manufacturing. So, do not expect the price of PV modules to significantly come down anymore. With almost zero gross margin, the future price of modules will stabilize and stay more or less constant at least until it aligns itself again, in some years, to the well-established experience curve. That will require a significant increase in cumulative installed capacity.

So, in the mean time, if the PV companies cannot compete on price anymore, what will they compete on? What would

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be the main decision factor for the customer? To answer this question, it is important to understand that, in the current context of a "buyer's market," customers have become extremely demanding on reliability. The PV industry has never seen such an increase in warranty claims as we observe today. At the same time, the accounts receivable of most PV companies has gone through the roof. Even if warranty claims are often a good excuse to defer payment, the reality is that the customers pay today much more attention to reliability than before. Large customers have the capabilities to test modules for performance and reliability. LID (light-induced degradation) and PID (potential-induced degradation) have become hot topics, and large customers are demanding independent certification for LID-free or PID-free performance. Reliability is now the No. 1 decision factor and the differentiation between PV companies. This is the first real sign of maturity of this industry, while we are still painfully going through adolescence.

Reliability

There is a fear among customers and bankers that the constant chase for lower production costs of PV modules is detrimental to the quality of the modules and will ultimately impact the reliability of PV systems. There is a fear that the most recent modules would not last as long as the modules made 20 years ago. This fear is quite legitimate, but it ignores the tremendous effort in R&D and the dramatic increase in experience, reliability data and material knowledge that the PV industry has accumulated for the last 35 years. It is clear for me that PV modules are much more reliable today than they were 20 years ago. However, there is always room for improvement, and PV companies that do not focus right now on reliability and failure analysis will suffer enormously from negative customer reactions that will force them to start a very painful and expensive recall program.

The next steps are innovation, innovation and … innovation! While reliability must be the No. 1 concern of PV companies, they will also have to innovate to improve efficiency, energy production rate and to reduce the LCOE (levelized cost of electricity).

Efficiency

For many years, the PV module was by far the most expensive element in the entire PV system, and the main selling argument was the price-to-power ratio ($/W). Nobody really cared about efficiency. Nowadays it is becoming clearer that efficiency is a significant parameter to reduce the cost of solar electricity. SunPower and Sanyo have been the first PV companies to realize it, but the rest of the PV industry is still focused on the price-to-power ratio ($/W) without paying too much attention to the real objective and the real sales argument of LCOE or $/kWh. Things are changing rapidly though: What I would call the "efficiency entry level" to the PV market is now well over 10 percent, compared to about 5 percent two decades ago. It is obvious that the "efficiency entry level" is increasing year after year, and would almost surely reach 15 percent in a few years. Efficiency, along with reliability, will become a key differentiation factor, particularly for markets like Japan and Europe. That is why the most innovative PV companies still have a chance to survive in these years of harsh competition.

Energy

Research and innovation to increase the "energy efficiency" of PV systems are similarly important. PV companies should start thinking not only about ways to improve the conversion efficiency (or power efficiency) of their modules, but ultimately about techniques to improve their energy efficiency, i.e., the ratio of kWh produced by the modules and kWh/m^2 of sunlight received over a one-year period. One of the most important factors is, of course, the temperature coefficient, which naturally is reduced as the voltage and the power efficiency increase. The most efficient modules usually demonstrate the best energy efficiency, but there are other ways to improve the energy efficiency of PV systems, including:

- Reducing the NOCT (normal operating cell temperature), for example, by improving the U-factor or thermal conductance of the PV-modules; improving the emissivity of backsheets; and reducing the absorptivity of cells by reflecting unused infrared light without impacting the power efficiency
- Improving the partial shading tolerance at the module level with integral bypass diodes or individual bypass diode for each cell, or at the system level with intelligent and efficient power optimizers
- Improving the maximum-power-point tracking software of inverters

As the conversion efficiency of the modules increases, trackers become more affordable and the capacity factor of power plants can be increased with one-axis or two-axis tracking. However, low-cost innovative trackers are still needed.

Levelized Cost of Electricity

In addition to improving the conversion efficiency and the energy efficiency, innovation also has a role to play to reduce LCOE, in particular by developing:

- Innovative module and rack design to reduce installation time and cost
- Smart modules to improve monitoring and reduce O&M costs

Conclusion

As of today, solar PV is moving from relying on subsidies toward grid parity in the coming decade. Partnership without borders and without barriers between the PV companies with great manufacturing

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skills and other PV companies or research centers that have mastered innovation will not only be beneficial for these companies but also for their customers, the entire PV industry as well as the environment.

As a scientist, I have always seen partnering with global peers as the seed for innovation. Global collaboration will stimulate the world's PV industry and accelerate its grid parity. That is what governments should promote. In the long run, competition between PV companies will focus not so much on the cost of power ($/W) but first on reliability and second on innovation, with the ultimate goal being reducing the cost of energy, i.e., the LCOE. In 2020, the surviving PV companies must be able to combine manufacturing skills and innovation. Ignoring one of these two aspects will be a sign of immaturity. ■

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NEW TECHNOLOGIES & MATERIALS

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New technologies and materials, as well as novel concepts for PV energy conversion, are actively being investigated globally to further drive down the $/W$_p$ cost of PV electricity generation. Following are two articles that fall into this category of R&D.

In the first article, a research team from Belgium, Czech Republic and Switzerland present the first results of their European Union funded "MOLESOL" project. The goal is the development of an improved dye-sensitized solar cell ("Grätzel cell"), whereby the dye monolayers are linked through organic molecular wires to a semiconducting thin film that is deposited onto a transparent substrate. The molecular wires improve charge carrier collection from the photoexcited dye molecules and thereby increase the cell's short-circuit current density. To enable higher open-circuit voltages, the traditional cathode of the Grätzel cell (a platinum film on an n-type TCO layer) will be replaced by a novel p-type semiconductor film, to obtain a better alignment of the energy levels of the dye molecule and the cathode's surface material. The first promising solar cell results with efficiencies of over 8 percent are reported for devices with a cathode surface coated with graphene nanoplatelets and an electrolyte consisting of cobalt-based redox couples.

In the second article, researchers from the University of Amsterdam are investigating the use of silicon nanocrystals to boost the efficiency of silicon-based solar cells, by modifying the solar spectrum "seen" by the devices. High-energy photons are "cut" into two or three photons with more ideal energy, while low-energy photons are upgraded to energies that can be converted by the solar cell. These processes occur via energy transfer between closely spaced nanocrystals. The nanocrystals are part of a thin overlayer that is placed between the sun and the solar cell. The authors provide interesting experimental evidence for the occurrence of energy transfer effects between neighboring silicon nanocrystals.

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Toward a Novel Generation of Thin Film Dye-Sensitized Solar Cells

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Abstract

In the context of the European FP7 project MOLESOL, a novel type of thin film solar cell is proposed that exploits properties of both organic solar cells and dye-sensitized solar cells. A first step on the road toward this low-cost, easy-to-fabricate, stable and highly efficient solar cell is described.

Introduction

Although crystalline silicon (c-) technologies continue to dominate the PV market, thin film technologies have made significant progress in grid-connected applications. Thin-film-based solar cells are potentially cheaper than, e.g., c-Si solar cells because of their lower materials costs and larger substrates. They generally show better performance under low light conditions and may offer particular design options for building integrated applications. The most mature thin film PV technologies use CIGS (copper indium gallium (di)selenide), a-Si or CdTe as photovoltaic material. Attractive but less mature alternatives are organic solar cells (OPV) and dye-sensitized solar cells (DSCs). OPV cell designs have recently made a significant step toward low-cost solar cell technology. But they still need to demonstrate long-term stability and power conversion efficiencies above 10 percent before they will be considered for large-scale production. Today the highest power conversion efficiencies for an organic solar cell based on a bulk heterojunction device with PCBM ([6,6]-phenyl-C61-butyric acid methyl ester) and low-bandgap conjugated polymers is 8.3 percent and, 10 percent using soluble small molecules – but this system seems reaching its limits. Offsets in the energetics lead to large internal energy losses. DSCs, on the other hand, perform better in terms of conversion efficiency, reaching efficiencies above 12-13 percent. Their key component is a dye-sensitized semiconductor anode and an electrolyte. However, problems with the stability of the electrolyte hinder widespread deployment.

It is our goal to develop a highly efficient molecular-wire charge transfer platform that can be used in a novel generation of thin film dye-sensitized solar cells fabricated via organic chemistry routes. By combining the advantages of both OPV and DSC concepts, this novel type of thin film solar cell will hence be low cost, easy to fabricate, stable and highly efficient. These developments are being carried out within the MOLESOL project, a collaborative project under the European 7th Framework Programme. In this article, we describe the visionary approach of the project, its challenges and first realizations.

The MOLESOL Approach

To explain our novel “MOLESOL” solar cell concept, we start from considering a generic DSC device, also called a Grätzel cell. Such a cell consists of a dye-sensitized TiO_2 photoanode (n-type), an electrolyte solution with a redox mediator and a cathode. The latter is typically a film of Pt nanoparticles on F-doped SnO_2 or indium tin oxide (Pt-FTO/ITO), and the former is the I_3^-/I^- redox couple in aprotic electrolyte medium. On photo-excitation, the dye (typically ruthenium based) injects an electron into the n-type material and the hole is captured by the electrolyte. The electrons then travel through the nanostructure to be collected as current at the external contact, while the holes are transported to the cathode by the redox shuttle in the electrolyte solution. This solar cell is an attractive alternative to

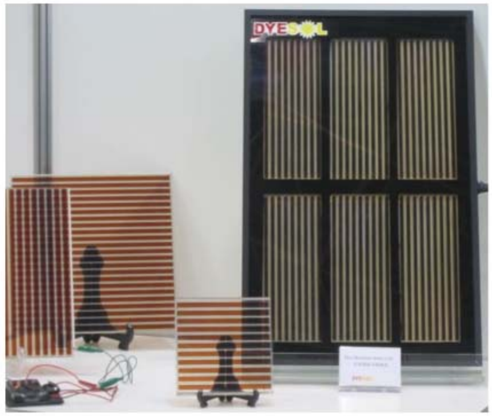

Figure 1 (a) – Dyesol Exhibition Booth at PV Expo in Japan, Showing Various Transparent and Opaque DSC Devices

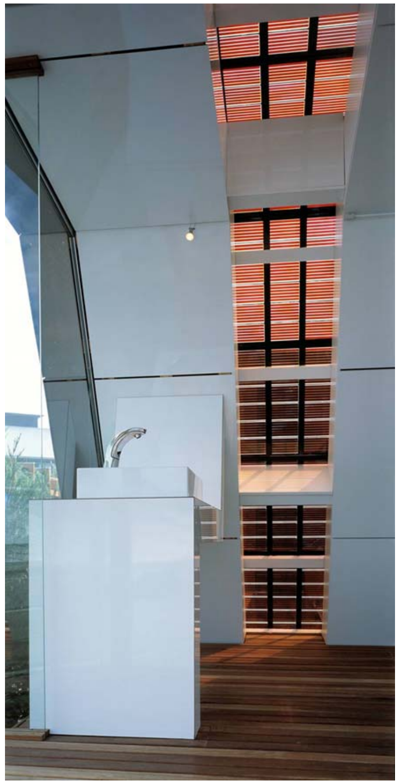

Figure 1 (b) – Photo by Thomas Bloch reproduced with permission of Innovarchi Pty. Ltd.
Courtesy of Dyesol Ltd.

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solid-state OPV due to its high efficiency, low cost and ease of fabrication. In view of large-scale production, the most important drawback of such a system is the instability of the electrolyte solution.

The technology proposed within the MOLESOL project makes use of assembled dye monolayers linked through organic molecular wires to a semiconducting thin film that is deposited on an optically transparent substrate. Short molecular wires will be used that are compatible with the exciton diffusion length. This way, the critical length for charge collection generated in the dye monolayer by the inorganic bottom electrode will be significantly reduced. In addition, the inorganic ITO/FTO n-type layer as used in a traditional DSC will be replaced by a novel transparent wideband p-type semiconductor that enables engineering of the surface work function, leading to a perfect match between the highest occupied molecular orbital (HOMO) of the dye layer and the valence band of the semiconductors. This opens routes to an increased open circuit voltage V$_{OC}$. For this purpose, the use of graphene and screen printing solutions will be investigated. The aim of this concept is to establish cost-effective, stable cells with enhanced conversion efficiency, scalable above 11 percent.

First Result: An Optimized DSC With Graphene Cathode

As a first step toward a novel hybrid solar cell, an optimized DSC has been developed in which graphene nanoplatelets (GNPs) in the form of optically transparent thin films on FTO have been used as a replacement for Pt-FTO. This graphene-based cathode was used in combination with Co-based redox couples as well as with the traditional I_3-/I- redox mediator.

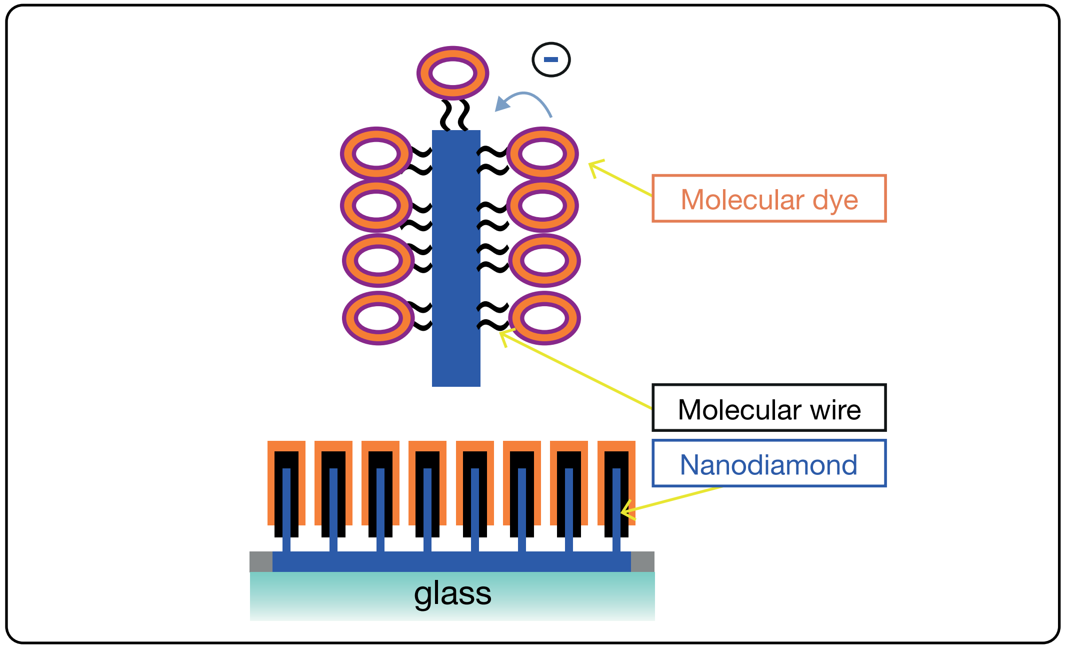

Figure 2 – Proposed Concept of the Molecular Wire Solar Cell

In a classical DSC, the role of the redox mediator I_3-/I- is to transport holes from the dye (adsorbed on the TiO$_2$ photoanode) through the electrolyte solution toward the optically transparent counter-electrode made from Pt-FTO. There is no other counter-electrode material superior to Pt-FTO in electrocatalytic activity for the I_3-/I- redox reaction, associated with the high optical transparency of the electrode. However, the redox potential of I_3-/I- is too low to achieve an optimum voltage of the DSC system, and consequently, to achieve the best power conversion efficiency. To address this subject, several other redox shuttles with more positive redox potentials were recently proposed. We found that Co-based redox couples, such as Co(L)$_2$ (where L is 6-(1H-pyrazole-1-yl)-2,2'-bipyridine) and Co(bpy)$_3^{3+/2+}$ (bpy = 2,2'-bipyridine) turned out to be particularly promising for this purpose.[1,2]

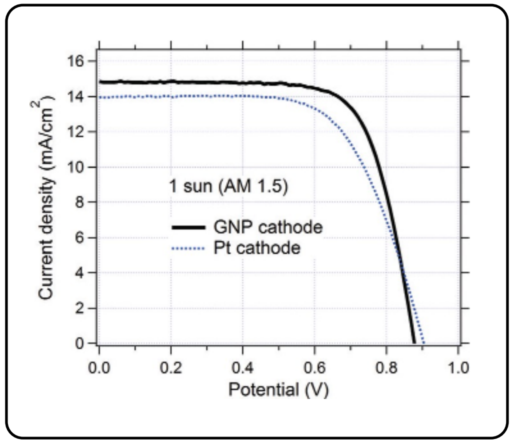

Figure 3 – Current-voltage characteristics of dye-sensitized solar cells with Y-123-sensitized TiO$_2$ photoanode and acetonitrile solution of Co(bpy)$_3^{3+/2+}$. Dotted line: DSC with Pt-FTO counterelectrode. Continuous line: DSC with GNP-FTO counterelectrode. The illumination intensity is 1 sun (AM 1.5).

We also showed that Pt-FTO is not necessarily the optimal cathode for Co-mediated DSCs. Moreover, although the amount of Pt on the cathode is very low, there is a demand for substituting Pt with a cheaper material. We found that graphene nanoplatelets in the form of a thin semitransparent film on FTO exhibit excellent activity in the Co-mediated DSC device.[3] GNPs exhibit high electrocatalytic activity for the mediator Co(L)$_2$ and even higher activity for Co(bpy)$_3^{3+/2+}$.[4] In the latter case, GNP is clearly outperforming the catalytic activity of Pt-FTO. The experiments were carried out by using Y123-sensitized TiO$_2$ photoanodes. The exchange current densities for the Co(III/II) redox reaction scaled linearly with the GNP film's optical absorbance, and they were by one to two orders of magnitude larger than those for the I_3-/I- couple on the same electrode. Dye-sensitized solar cells achieved energy conversion efficiencies between 8 to 10 percent for both GNP and Pt-based cathodes. However, the cell with GNP cathode is superior to that with Pt-FTO cathode, particularly in fill factors and in power conversion efficiencies at higher illumination intensities. This finding has a straightforward application in the design of a novel type of dye-sensitized solar cells.

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Conclusion

A new European project called MOLESOL has been set up to demonstrate a revolutionary pathway for fabricating low-cost, high-efficiency and stable solar cells. The envisaged solar cell will be a hybrid device that consists of dye monolayers that are linked through an organic molecular wire to a semiconducting thin film deposited on a transparent substrate.

As a first step toward this goal, the Pt-ITO/FTO electrode used in conventional DSC-type solar cells will be replaced by graphene. The first result in this context is the development of an optimized DSC with a cathode based on graphene platelets interfaced to Co-based redox mediators. DSCs with these materials reached conversion efficiencies between 8 to 10 percent.

This three-year European FP7 project started in October 2010. Project partners are imec/IMOMEC, Belgium; Solarprint Limited, Ireland; Ustav Fyzikalni Chemie J. Heyrovskeho AV CR, v.v.i., Czech Republic; Dyesol Italia, Italy; Max Planck Gesellschaft Zur Foerderung der Wissenschaften E.V., Germany; Linkopings Universiteit, Sweden; Ecole Polytechnique Federale de Lausanne, Switzerland; and National University of Singapore, Singapore. Imec/IMOMEC is project coordinator. More information on the MOLESOL project can be found on www.molesol.eu.

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Shaping the Solar Spectrum With Si Nanocrystals

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Abstract

To overcome the current limit of photovoltaic conversion efficiency arising for Si-based solar cells due to the broad spectral range of the solar radiation, Si nanocrystals (Si NCs) can be implemented. These can "shape" the solar spectrum to the range more appropriate for conversion. In addition, Si NCs can also "cut" high-energy photons into multiple smaller ones and have potential to utilize low-energy photons that are generally lost in present-day solar devices.

The conversion efficiency of the "first generation" wafer-based photovoltaic devices is strongly limited by the mismatch between the broad band of photon energies available in the solar spectrum and the optimum conversion energy range determined by the physical parameters of the active material. Currently, several options are available, such as (low-efficiency) organic cells or multi-junction tandem configurations, which can reach efficiencies of ~45 percent, but are relatively expensive. However, the practical application of almost all of these is often hampered by such factors as high cost, fast degradation, complex and expensive manufacturing procedure, and toxicity. The latter issue is especially important in view of the recent regulations concerning use of hazardous materials and health restrictions.

Presently, the majority of photovoltaic devices are Si based, with the highest efficiency reaching toward 28 percent, close to the theoretical limit of ~31 percent.[1] Silicon has very advantageous properties, such as the appropriate band gap energy, non-toxic nature, large abundance (approximately one-third of the Earth's crust is Si) and superior stability. However, while Si-based solar cells feature very good conversion efficiency in the visible regime, considerable losses appear for photons in the UV (by heat generation) and in the (N)IR, where all the photons escape the absorption. A possible remedy to this problem can be found by implementation of Si nanocrystals (Si NCs) into existing Si-based solar cell configurations. In general, NCs offer some major advantages, such as band structure tuning, reduction of carrier cooling by electron-phonon scattering, and enhancement of surface-related effects, all of which are relevant for energy transfer and/or carrier recombination mechanisms and could influence conversion efficiency. In particu-

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lar, Si NCs are able to transform the broad range of solar photon energies into the range of maximum conversion efficiency of the conventional Si solar cell.[2]

What makes Si NCs exceptionally interesting in comparison to NCs of other semiconductors with similar band gap energies is that in a particular configuration, an efficient carrier multiplication process can take place. This was observed for the first time several years ago in Si NCs dispersed in a SiO_2-matrix[3] and recently quantified to exhibit efficiency of ~100 percent.[4] In the relevant experiment, it was shown that the photoluminescence (PL) quantum yield (i.e., number of emitted versus absorbed photons) increased above a certain threshold energy of incoming photons, implying that excitation by a single high-energy photon can result in two (or more) emitted photons. Since upon pulsed excitation every Si NC can emit a maximum of a single photon, independent of the incoming photon flux, it was derived that the enhanced emission originated from different NCs excited by the same photon (see Figure 1a for a schematic illustration). This "*space-separated quantum cutting*" (SSQC) process has been confirmed recently by induced absorption (IA) experiments, in which not the photon emission but the concentration of carriers generated by pho-

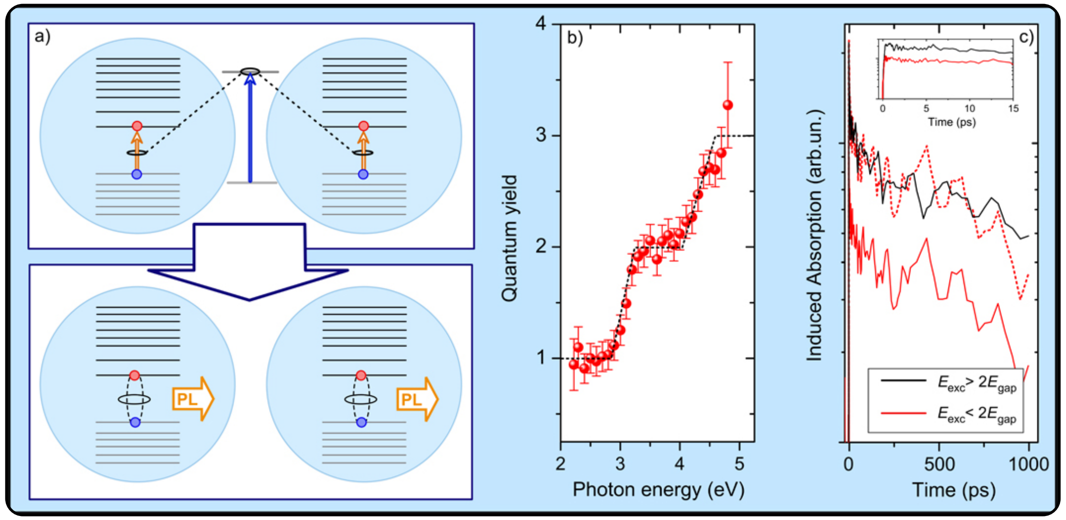

Figure 1 – Carrier multiplication with Si NCs. a) schematic illustration of simultaneous excitation of 2 separate NCs by a high-energy photon. In this picture, the excitation precedes via a "virtual" state, energetically coupling 2 (or more) NCs. The 2 NCs both get to the excited state and are able to emit a photon; b) photoluminescence quantum yield, which increases in a steplike manner with photon energy, reaching 200% and even 300% of its initial value when photon energy exceeds a threshold of $E_{exc}>2E_{gap}$ and $E_{exc}>3E_{gap}$, respectively; c) induced absorption signal (reflecting concentration of free carriers) for high- ($E_{exc}>2E_{gap}$ – black) and low- ($E_{exc}<2E_{gap}$ – red) photon energy excitation in the low-flux regime of less than 1 absorbed photon per NC. When normalized, it is evident that dynamics are very similar (see the dashed red line). The inset displays the first few picoseconds of the dynamics, showing no difference in buildup of the signal for the 2 different excitation conditions.

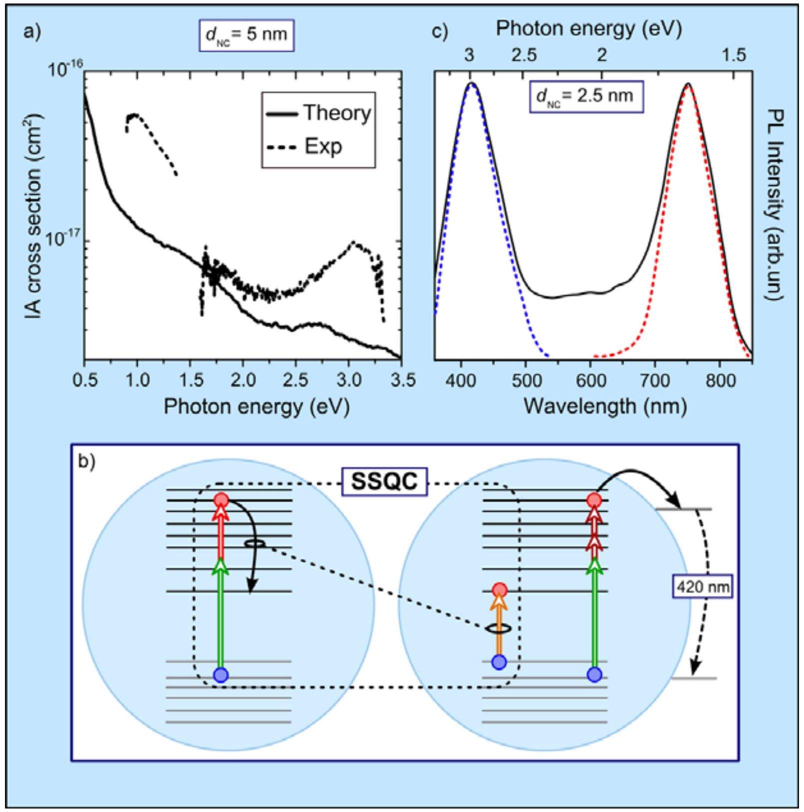

Figure 2 – Induced absorption, and photoluminescence results of Si NCs combined with a schematic illustration of (N)IR photon absorption scenarios. a) theoretical modeling (black solid curve) and experimentally obtained (black dashed line) IA cross section for Si NCs with average diameter of d_{NC} = 5 nm for detection photon energies between E_{det} = 0.5-2.5 eV upon (pulsed) excitation with E_{exc} = 3.5 eV. Experimental results coincide with theoretical simulations for the visible regime, but are about a factor of 5-10 higher in the low-photon energy regime; b) schematic illustrations of sequential absorption of multiple photons of high and low energy. Left panel: When combined energy is sufficient (i.e., E_{exc} <$2E_{gap}$), a neighboring unexcited NC can get excited, by which energy is distributed over more NCs by means of the SSQC process. Another scenario is the creation of a hot carrier by absorption of multiple "small" photons, which then get trapped at a defect level at the surface of the NC. Recombination of carriers from this defect center results in an emission centered at ~420 nm. Right panel: NCs with different band gap sizes (but with the fixed 420 nm line) could be used to have IR photons absorbed and the created hot carriers trapped; c) spectral profile of PL dynamics constructed for t = 0 (i.e., during excitation pulse) for Si NCs with average diameter of d_{NC} = 2.5 nm upon excitation with a 2 ps pulsed laser operating at E_{exc} = 3.8 eV. The spectrum consists of 2 major contributions centered at ~750 nm (red dashed line) and ~420 nm (blue dashed line), respectively. The former is related to band-to-band recombination of excitons, whereas the latter is related to recombination of hot carriers trapped at a defect level at the surface of the Si NC.

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ton absorption is directly measured. It was found that while the carrier dynamics were identical for low- and high-photon energy excitation (carefully normalized for the same number of absorbed photons), the respective concentrations increased (see Figure 1c).[5] Moreover, these ultra-fast experiments showed that the carrier multiplication process was occurring "instantaneously," i.e., faster than the resolution of the setup ($\tau_{res} \approx 100$ fs).

In addition to the above-described "photon cutting" process, Si NCs also offer the possibility of enhancing conversion efficiency by utilizing the low-energy photons in the (N)IR regime of the solar spectrum, which are lost in a conventional Si-based solar cell. The absorption cross section for these photons is either zero (for "sub-band gap" energies) or very low (for energies just above the band gap) as a consequence of the indirect band gap structure. Nevertheless, their absorption can proceed via non-linear ("induced") absorption (IA) by free carriers in the bands. It has been found that in case of Si NCs, this process is significantly enhanced compared to bulk Si, with the absorption cross sections being factor 10-100 larger. Figure 2a demonstrates the theoretically modeled (black solid line) and experimentally obtained (black dashed line) IA cross section as a function of probing photon energy for Si NCs with an average diameter of $d_{NC} = 5$ nm under (pulsed) excitation with $E_{exc} = 3.5$ eV. In the visible regime, the experimental results are rather consistent with the modeled values (up to certain threshold energy related to formation of a self-trapped exciton in these Si NCs).[6] In the low-photon energy regime, however, the experimental values are significantly higher than the theoretical simulations. Figure 2b schematically illustrates possible scenarios for non-linear photon absorption of low-energy photons: absorption of a photon in the visible regime is followed by (or proceeds simultaneously with) absorption of a low-energy photon (or photons) with energy smaller than the Si NC band gap. Theoretically, when their combined energy exceeds twice the NC band gap, the possibility of the earlier-discussed "photon cutting" process could arise, with energy transfer to a neighboring NC. Another scenario is the sequential absorption of a high- and (a) low-energy photon(s) by which hot carriers are created; these carriers could then be trapped at defects at the surface of the NC. Identification of such a defect center is shown in Figure 2c for the sample with average NC diameter of $d_{NC} = 2.5$ nm, where the spectral profile for PL dynamics in the visible regime is illustrated during the (picosecond UV) excitation pulse. The spectral profile reveals two major contributions: next to the conventional excitonic emission centered around $\lambda_{PL} \approx 750$ nm ($E_{PL} \approx 1.65$ eV and microsecond decay), another PL band around $\lambda_{PL} \approx 420$ nm ($E_{PL} \approx 2.95$ eV) and with nanosecond decay can be observed.[7] Since this emission is defect related, its spectral position is (practically) independent on NC size. Potentially, this would allow for optimization of absorption of specific IR photons by tuning the NC size for the optimal band gap energy (Figure 2b, right panel).

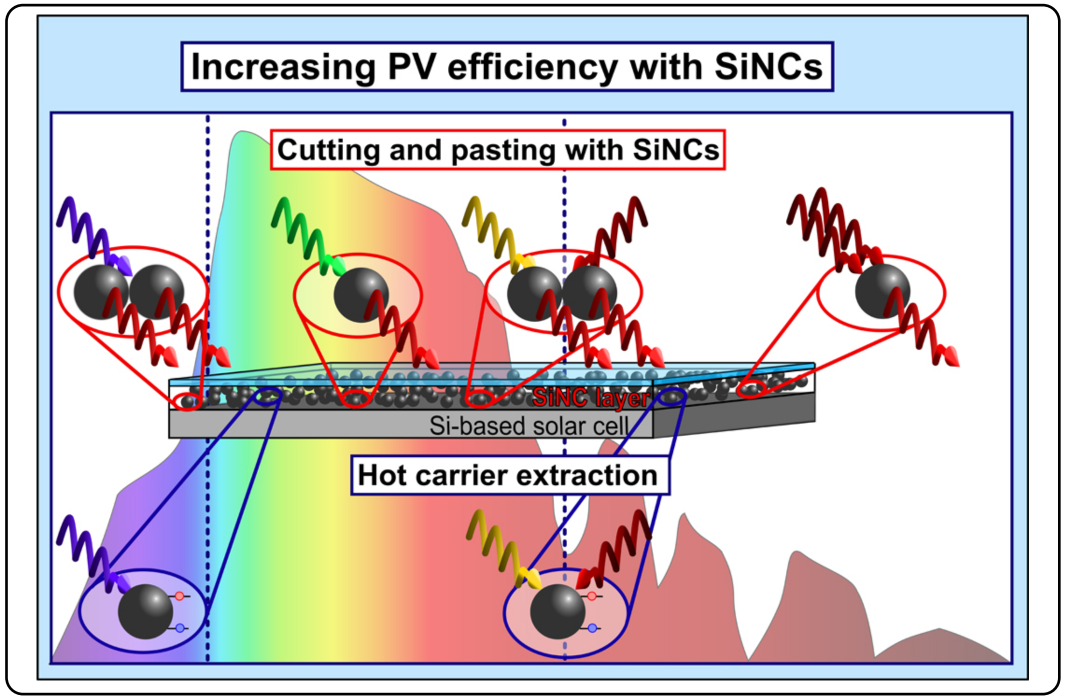

Figure 3 – Spectral shaping with Si NCs. On the high-photon energy part of the solar spectrum, the Si NCs can efficiently convert photons by SSQC with ~100% efficiency. For photons with energy slightly smaller than twice the band gap, but which generate carriers with large excess energy, trapping of hot carriers can recombine via the 420 nm line. In the visible regime, photons can be converted to the appropriate range for optimal conversion. For the photons with low energy, Si NCs can be excited by multiple photons or in combination with photon of higher energy by which a hot carrier is created.

Currently, the possible scenarios for incorporation of quantum dots (QDs) or NCs in photovoltaic devices are explosively developing. Recently, it has been shown that for a PbSe-QDs-based solar cell, external photocurrent quantum efficiency can exceed 100 percent by means of efficient carrier multiplication.[8] In this case, the carrier multiplication occurs in one and the same QD, and following that event, the carriers are extracted. Since the quantum confinement induces enhancement of Coulombic interaction between carriers, the lifetime of the generated multiple carriers is extremely short (on the picosecond time scale), rendering the extraction of carriers very challenging. In case of Si NCs, where the multiple carriers are created in separate (neighboring) NCs, the carrier-carrier (Auger) interaction is suppressed and lifetime of the carriers is governed by their radiative recombination, on the order of 10-100 μs. This is directly evidenced by the lack of Auger-related components in carrier dynamics recorded for high-photon energy excitation (see Figure 1c). This opens prospects for an easier and efficient extraction of carriers. In this scenario, the trapping of hot carriers at the "420 nm defect" offers the possibility of draining carriers with

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large excess energy prior to cooling, opening a potential route toward the so-called *hot carrier solar cells* (see lower part of Figure 3). In addition, as previously mentioned, Si NCs can shift those photon energies within the solar spectrum that cannot be optimally converted in the current Si-based solar devices to the appropriate range and in this way overcome the significant efficiency losses (see Figure 3, upper part). Therefore, by channeling the incoming photons into two streams – the high-energy stream at 420 nm (defects), and the low-energy stream at the band gap energy (NIR) – an ultimate spectral shaper could be developed. By material and process optimization, the relative importance of these two channels could be tuned; in a practical photovoltaic device, these two streams could be fed into separately optimized convertors.

In summary, due to their conversion and “photon cutting” capacities, Si NCs emerge as promising candidates for different PV scenarios of third-generation solar cells. Ideally, a Si NC coating layer could be added (as depicted in Figure 3), where the incorporation of these Si NCs are implemented in currently available solar cell preparation techniques, rendering additional costs extremely low. Current and future research urgently needs to verify the feasibility of these attractive prospects!

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Wieteke D.A.M. de Boer *(1983) studied condensed matter science at the University of Amsterdam and finished her master project in the group of Tom Gregorkiewicz. The research concerned spectrally and time-resolved optical spectroscopy on silicon nanocrystals, a topic she continued as a Ph.D. student in the same group.*

Tom Gregorkiewicz *studied physics at the University of Warschau. After his promotion (1980) and habilitation at the Polish Academy of Science, he started working at the University of Amsterdam (1989). In 2003, Dr. Gregorkiewicz became professor of the Optoelectronic Materials group at the Van der Waals–Zeeman Institute. The research of the group concerns optical and photonic properties of silicon and germanium in different configurations.*

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WAFER SILICON PHOTOVOLTAICS

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Kristian Peter
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Crystalline silicon cells and modules

Over the last few years, crystalline silicon PV has deployed at a faster rate than previously expected. The result in these times is a tremendous production overcapacity, and companies are forced to sell PV products below production prices accordingly. New markets are therefore important and it is only a question of time until the demand for solar modules and systems again will increase.

It is expected that several countries will launch programs to increase the share of electricity from PV. In Japan, the new feed-in tariff system for solar took effect in July 2012, and Germany’s feed-in tariff scheme will continue without volume limitations until the cumulative PV capacity reaches 52 GW.

In difficult business times, it is advisable to concentrate on research and development to increase efficiency and decrease production cost for PV cells and modules. Improved crystallization techniques and advanced cell concepts such as selective emitters, local rear-contact schemes, n-type cells and fully rear-contacted cells are the results of recent cell and module developments.

The two main types of silicon used in solar cells are monocrystalline and multicrystalline silicon. Mono-like silicon merges these two manufacturing processes. The nucleation-growth casting process produces silicon solar ingots ready for dicing and slicing. The use of the resulting full square quasi-mono wafers with preferred (100) crystal orientation is one option to increase the efficiency of solar panels while maintaining the production cost at low level.

Researchers from the School of Photovoltaics at Nanchang University (China) explain the main challenges and problems to be solved related to the use of monocrystalline-like ingot growth and suggest a solution to lower the thermal stress by engineering the liquid/solid interface.

If successful, the approach for mono-like silicon ingot growth may contribute to making the total PV system cost low enough to achieve competitive electricity prices in most (industry) regions in the world.

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Monocrystalline-Like Cast Silicon: Promising While Challenging

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Abstract

The apparently promising monocrystalline-like cast silicon has not yet reached its expected commercialization scale since its pilot in 2010. Two major technical challenges are identified: the need to obtain 100 percent monocrystalline wafers; and the hope of achieving higher cell efficiency by reducing dislocations in the cast monocrystalline silicon, which is found to consist of subgrains. A solution to meet the challenges is suggested.

Introduction

The monocrystalline-like cast silicon is produced in basically the same process as directional solidification of multicrystalline cast silicon, but seeded with (001) monocrystalline silicon on the bottom of the mold. The resultant ingot is not 100 percent monocrystalline, but composed of a large central monocrystalline part and the surrounding multicrystalline part. Compared with the conventional seed-free directional solidification of multicrystalline silicon, more sophisticated thermal control and longer processes are required. The added cost comes mainly from the seed crystals and the longer process. Pilot production of the cast monocrystalline-like silicon ingots and the solar cells based on this new material started in 2010. At that time, this new technology appeared overwhelmingly advantageous over the existing mainstream technologies – cast multicrystalline silicon and CZ monocrystalline silicon. Briefly, it offers conversion efficiency similar to that of CZ monocrystalline silicon, with the cost similar to that of multicrystalline silicon, while free of CZ monocrystalline silicon's disadvantages due to high oxygen content and round cross-sectional geometry. However, as we see today, its expected dominance in the PV industry have not taken place, though slow gradual developments are occurring.

In fact, interestingly, the effort of seeded directional growth of monocrystalline silicon ingots, following success in seeded directional growth of sapphire, preceded development of today's seed-free multicrystalline silicon, in the 1970s.[1] The real history is that monocrystalline-like silicon was denied and multicrystalline silicon was chosen. Was the choice an unfortunate mistake from today's view, or the other way around: Is today's development a repeated mistake from a historical view?

The basic message from this piece of history is explicit to us: Development of the monocrystalline-like silicon is not going to be easy. The last two years' experience is an indication. The challenges are not only from the cost, but physics of materials as well. This article reports our observations focused on the latter, through our experimental studies, literature and communications with the industry.

Challenge One: To Be Mono Rather Than Mono-Like

Compared with the conventional seed-free directional growth of multicrystalline silicon, the required variation in thermal field and process for growth of the monocrystalline-like silicon, or mono-like silicon, as the industry call it, is not as great, and preliminary success with furnaces for production of conventional multicrystalline ingots have been claimed by many companies, while specialized furnaces have recently been developed and put into market.

By "preliminary success," we mean that, taking the current mainstream G5 ingot (its square plane allows 5 x 5 wafers of 156 x 156 mm^2 size) as an example, the central monocrystalline part of the produced ingot is large enough so that on any wafering plane of the ingot, 3 x 3 wafers of pure monocrystalline silicon can be obtained from the total number of 5 x 5 wafers. Such a big monocrystal (cross-section area >470 x 470 mm^2) is indeed quite satisfactory for a developer from multicrystalline silicon production. Unfortunately, commercial practices of this new technology show that to well justify its added cost, this percentage is not enough; rather, a yield of 100 percent monocrystalline wafers is required. Because the remaining 16 wafers of mixed crystalline states are usually not better than normal multicrystalline wafers, and their strange appearance makes them less acceptable in the market.

The desired state simply means mono rather than mono-like crystalline silicon cast. To achieve this goal, nucleation of crystals on walls of the cast mold must be prevented or the growth from the crystals nucleated on the walls, if any, must be limited to the surface cutoff range of the ingot, which is about 30 mm thick. This is not realized yet on a commercial scale, though a company in China claimed success in the R&D stage.[2]

Challenge Two: To Be Less Defective

The second major challenge is about the crystallization quality of the monocrystalline part of the ingot. It can be mostly measured by the dislocation density of the crystal. Dislocations are the defects most detrimental to photovoltaic performance of crystalline silicon. The much higher dislocation density in multicrystalline silicon than that in CZ monocrystalline silicon defects, rather than the presence of grain boundaries, is believed to be the major reason, apart from less efficient surface texture, for the poorer photovoltaic performance of the multicrystalline silicon.

However, being monocrystalline does not ensure lower dislocation density. Figure 1 shows a set of micrographs of the monocrystalline part of silicon in a common commercial monocrystalline-like sil-

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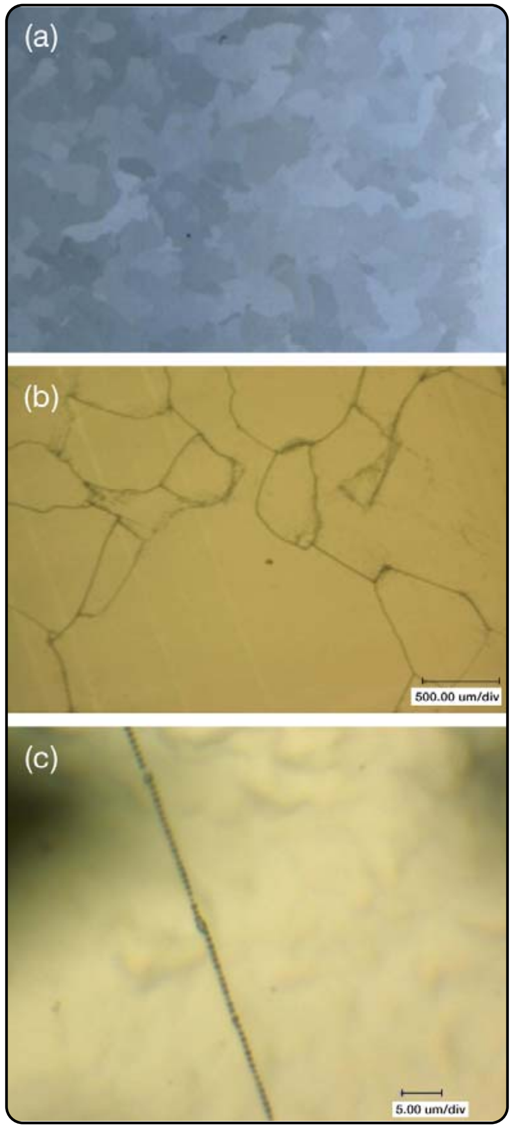

Figure 1 – Micrographs of monocrystalline – part of a commercial monocrystalline-like silicon ingot: a) scanned image of alkaline textured surface (27 x 21 mm^2); b) optical micrograph of polished and dislocation pit-etched surface (the straight parallel light strips are cutting traces created in wafering); c) a closer view of a subgrain boundary with distinguishable dislocation pits

icon ingot. As can be seen, the monocrystal actually consists of subgrains of millimeters size, which after alkaline surface texturing, shows visible contrast to the naked eye or under an ordinary scanner (Figure 1a), and the subgrain boundaries are well etched by the specialized etchant for revealing dislocations (Figure 2a).

According to the existing theory of dislocations, subgrain boundaries are low-angle grain boundaries consisting of arrays of dislocations, with their density proportional to the misorientation angle between the neighboring subgrains. An estimation with the theory shows that a relatively small misorientation angle of 3° corresponds to a dislocation distance of a few nanometers in the dislocation array, which is far from distinguishable by the present etch-pit technique. Only those of very low angle subgrain boundaries can have a visible array of dislocation etch-pit. Figure 1c indicates such a case.

While for most of the subgrains, to have the contrast distinguishable by the naked eye (as shown in Figure 1a), the misorientation angle between them must be over 3°. A rough estimation of the dislocation density, assuming square-column-shaped subgrains and [001] tilt misorientations, gives the density in number of dislocation per unit area, ρ, as

$$\rho = \frac{2\theta}{bd}$$

where θ is the average misorientation angle, d the average subgrain size and b the Burgers vector of the dislocation, which equals 0.385 nm for silicon. Table 1 gives the estimated dislocation densities for reasonable ranges of subgrain misorientations and sizes. They are even higher than the typical range of dislocation densities in normal multicrystalline silicon (on the order of 10^6/cm^2), if the large-angle grain boundaries in the latter are not counted as any contributions to the dislocation density. Indeed, it is true that large-angle (>10°) grain boundaries contain no dislocation structures geometrically, and electrically they have been found less detrimental than low-angle grain boundaries.[3]

Currently, about a 0.5-1.0 percent absolute increment in conversion efficiency has been reported for the cells made with the monocrystalline silicon wafers, as compared to those made with cast multicrystalline silicon wafers. The monocrystalline silicon, regardless of its dislocation density, has a unique advantage of forming a pyramid-like surface texture by cheap alkaline etching (~12 percent light reflection), while multicrystalline silicon can only form a pit-like surface texture by acidic etching (~25 percent light reflection). The benefit from such texture is about 13 percent less reflection of light. When an anti-reflection coating is applied, which draws down the reflectance at and near a certain wavelength, the above benefit is reduced to about a third, to about 4.3 percent, according to an estimation given by Green.[4] This benefit will lead to an absolute increment of 0.043Y in cell efficiency, where Y represents net efficiency of the cell, i.e., the efficiency taking into account the light loss from reflection. If the net efficiency of mono-like cells is the same as multicrystalline cells – 17 percent currently, which is equivalent to a net efficiency of 18.5 percent – the above benefit alone will generate about 0.8 percent absolute increment in their efficiency.

Average subgrain size (mm)		3	5	7
Average	3°	0.90	0.54	0.38
Misorientation	5°	1.50	0.90	0.64
Angle	7°	2.10	1.20	0.90

Table 1 – Estimation of Dislocation Density in the Monocrystalline Part of the Mono-like Silicon Ingot (in 10^7/cm^2)

So the currently reported increment in cell efficiency is about the same as that of a mere change of the surface texture from the pit-like to the pyramid-like would create. So we conclude that the current benefit of the cast monocrystalline silicon is mostly solely from its alkalinic surface texture. The fact that surface texturing by reactive ion etching (RIE) of multicrystalline silicon was found to boost 4-7 percent relatively of its cell efficiency as compared to the acidic texturing[5,6] supports this point, too, simply because RIE can generate textures of very low light reflectance on multicrystalline silicon. Therefore, we suggest that currently produced cast monocrystalline silicon is not less defective than cast multicrystalline silicon, and that further benefit from better crystallization quality of the cast monocrystalline silicon remains to be exploited.

A Suggested Solution

The problems from the two major challenges may be solved together by maintaining a convexed liquid/solid interface, as illustrated in Figure 2. First, due to simple geometrical rule, the growth of the (001) monocrystal tends to expand, while the growth of the crystals nucleated on the mold tend to shrink if the liquid/solid interface is so convexed. The red dotted line in Figure 2 indicates the boundary

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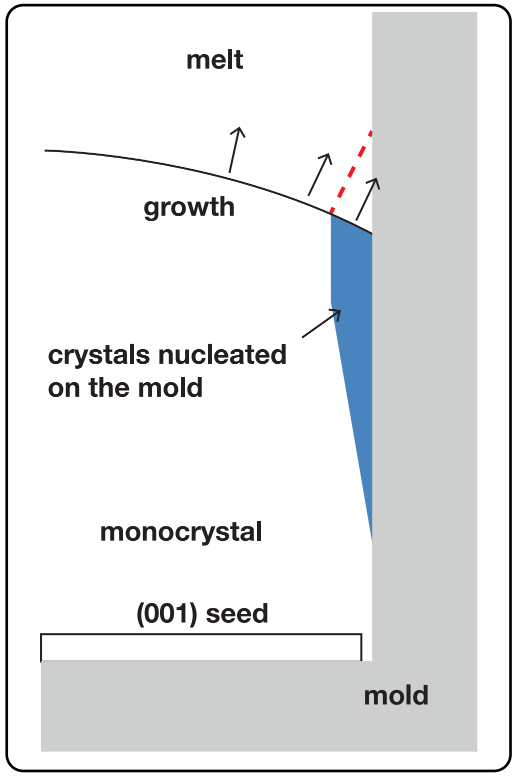

Figure 2 – An Illustration of the Growth of the Seeded Monocrystal vs. the Growth of the Crystals Nucleated on the Mold

between them in the forthcoming growth, if no preferential development of any part exists. Secondly, solidification of silicon, accompanied by volume expansion, at a convexed front, is less confined as compared with the growth at a concaved or a flat front. A lower level of thermal stresses, and hence lower dislocation density, is thus expected when a convexed liquid/solid interface is maintained.

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THIN FILM PHOTOVOLTAICS

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Reduced costs for direct materials were initially considered one distinct advantage of thin film photovoltaics (PV). Meanwhile, module efficiency and manufacturing costs are the key drivers for its market penetration. Among thin film technologies, copper indium gallium selenide (CIGS) has shown the highest efficiency potential in various applications. Several companies have started large-scale production worldwide, but further improvement in module performance is needed to survive in the competitive PV market. Repeatedly, similarities to the integrated circuit (IC) industry are discussed.[1]

P. Haldar and U. Pillai of the College of Nanoscale Science and Engineering (CNSE) – the former also an executive at the U.S. Photovoltaic Manufacturing Consortium (PVMC) – emphasize the importance of specialization and consortia for the PV industry.

The growing share of solar in the U.S. energy mix with increasing price pressure for PV modules is outlined. To achieve the aggressive cost goals, innovations of each segment of the solar value chain are needed. CIGS is considered to offer the greatest potential for the lowest cost of ownership among thin film technologies with environmental advantages.

A specialization similar to the semiconductor industry is an important factor to further advance the PV industry. Some suppliers who already specialize in CIGS equipment are mentioned.

Another analogy to the IC business is consortia that align consumer demands. Currently, a wide variety of CIGS products are available on the market. The CNSE has a leadership role in coordinating the research and manufacturing activities of semiconductor firms. Consequently, the PVMC was headquartered at CNSE to organize activities for the CIGS technology. The consortium also offers lab-to-fab capabilities that support fast commercialization of new technologies. For the CIGS technology, five technical opportunities were prioritized: (1) time-to-market; (2) time-to-volume; (3) product reliability; (4) balance of system; and (5) fab productivity. I look forward to seeing a roadmap format similar to that of the International Technology Roadmap for Semiconductors.

1. D. Jimenez, "PV Manufacturing: More Like Making Potato Chips or Computer Chips?" Future Photovoltaics, vol. 7, 2012.

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Vertical Specialization and the Role of Consortia in the Solar Photovoltaic Industry

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The solar photovoltaic industry has grown tremendously over the last decade. Worldwide annual solar cell production increased from 370 MW in 2001 to 27,000 MW in 2010. This rapid growth was driven in part by support programs for solar offered by governments across the world, and in part by the reduction in prices of PV systems.

While the industry has grown rapidly, it still accounts for only a very small fraction of total electricity production. In the United States, solar PV currently makes up less than 0.1 percent of total electricity production. During the last decade, governments around the world have undertaken many initiatives to make solar photovoltaics a more significant contributor to electricity generation. For example, the SunShot initiative of the U.S. Department of Energy (DOE) envisages solar reaching 303 GW of total installations by 2030 and 632 GW by 2050, which would make it account for 14 percent of total electricity generation in 2030 and 27 percent by 2050. To achieve this target, many barriers have to be overcome. A crucial element is the reduction in price of solar modules. The current average price of approximately $1/watt of solar modules is more than the $0.50 per watt required to meet the targets under the DOE's SunShot initiative. Reaching the target will require more innovations in solar manufacturing technology.

The declines in price of solar modules from $100 per watt in the 1960s to around $1 per watt today have come about as a result of improvements in technology over a period of 50 years. Further cost reduction to the target of $0.50 per watt is likely to be more difficult and can result only from innovations in each segment of the solar value chain – in materials, capital equipment, manufacturing processes, design improvements in cells and installation techniques. Attaining these difficult innovations is going to require specialized effort from companies and experts focusing on specific problems. The importance of specialization to manufacturing productivity has been known to economists for centuries, and was immortalized by Adam Smith in 1776 in his description of the manufacturing process in a pin factory – "One man draws out the wire, another straights it, a third cuts it, a fourth points it, a fifth grinds it at the top for receiving the head: to make the head requires two or three distinct operations: to put it on is a peculiar business, to whiten the pins is another ... and the important business of making a pin is, in this manner, divided into about eighteen distinct operations, which in some manufactories are all performed by distinct hands, though in others the same man will sometimes perform two or three of them." Smith recognized from his study of the pin factory that manufacturing productivity could be increased through specialization.

In modern economies where products are much more sophisticated than pins, these distinct activities tend to be undertaken by specialized firms rather than specialized workers. However, emerging solar firms making thin film modules do not yet have this specialization and therefore generally prefer to act as materials suppliers, equipment manufacturers, module makers and installers. As the market expands and competitive pressure intensifies, the demand for specialized services will increase in the thin film solar industry.

In the manufacture of products like solar modules, specialization brings

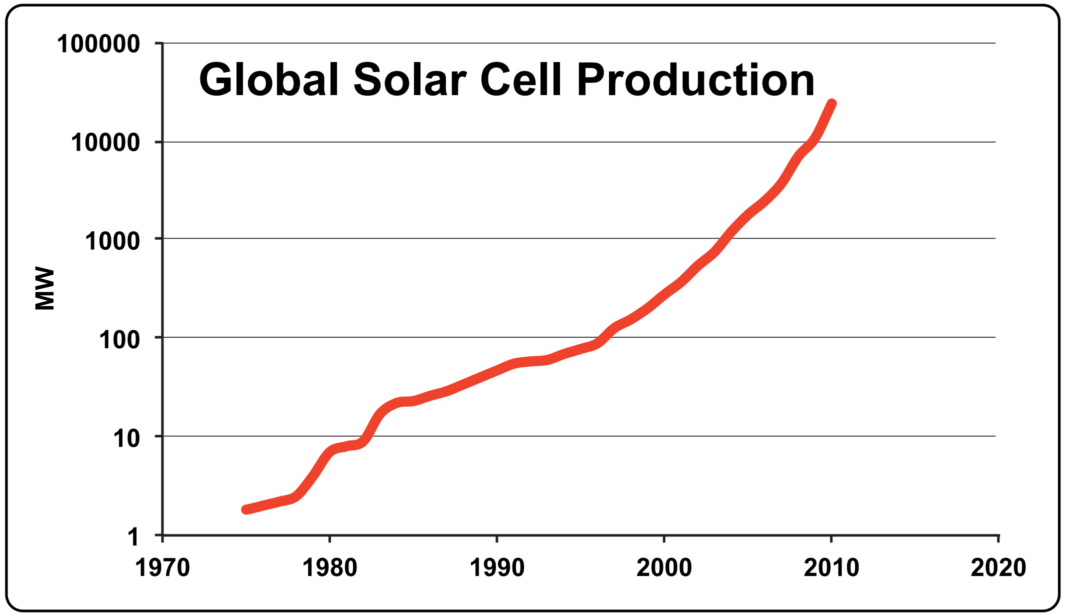

Figure 1 – Rapid Growth of Solar PV Cells Worldwide

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along a cost. The activities of the specialists have to be coordinated so that the whole process can run seamlessly, a process which is perhaps more difficult in modern-day manufacturing of solar cells than in 18th-century pin factories. This is especially difficult if rapid innovations are required along the whole value chain. To make a successful improvement in the final solar module, the activities of materials suppliers, equipment makers and module manufacturers have to be coordinated to ensure they are compatible with each other. Such coordination is all the more important when the industry is still experimenting to understand the “right” product, the one that will satisfy consumer demands. Firms will have to be nimble and respond quickly to the feedback they get from consumers, who will buy or reject the new product offerings. This phase of product experimentation and manufacturing process adjustments calls for a forum where firms can share information, collaborate effectively and respond quickly to consumer signals. The U.S. Photovoltaic Manufacturing Consortium (PVMC) – headquartered at the College of Nanoscale Science and Engineering (CNSE) in Albany, New York – was established to provide these coordination facilities to the emerging thin film copper indium gallium selinide (CIGS) technology.

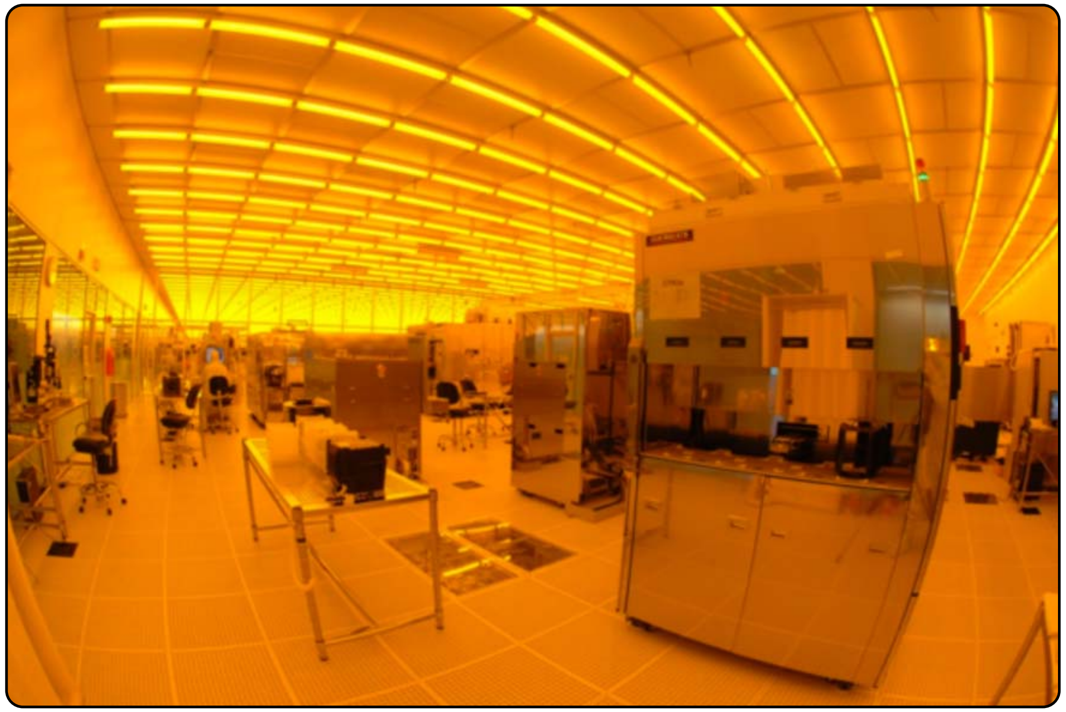

Figure 2 – A 300 mm Fab at the College of Nanoscale Science and Engineering

A classic example of the benefits of specialization and improved value chain coordination can be seen in the semiconductor industry. The early semiconductor manufacturers acted as a single-shop manufacturing facility, doing everything from materials improvement, equipment manufacturing, design and manufacturing of chips. As the industry grew, specialized firms emerged along the value chain to meet the demands of the increasingly complex manufacturing process. These specialized firms were often spun off from the divisions of the big firms. The equipment firms in the semiconductor industry like ASML, Applied Materials and KLA-Tencor have become a crucial part of the semiconductor supply chain. The innovations by these companies have become critical for advancing semiconductor technology, as important as the innovations made by chip manufacturing companies like Intel or IBM. This specialization in roles was an important contributor to the advancement of semiconductor technology, which in turn drove the expansion of the semiconductor product market.

But this specialization has come with costs of its own. Within two decades, the specialization had led to the emergence of a sophisticated, but unwieldy, supply chain. With numerous firms along the supply chain focusing intensely on their individual components and materials, ensuring compatibility of individual innovations became a difficult task. The first attempt at tackling this problem was taken by the Japanese government when the Ministry of Trade and Industry (MITI) set up the Very Large Scale Integration (VLSI) consortia to help diverse Japanese semiconductor manufacturers coordinate their research. In the 1980s, the Japanese semiconductor industry catapulted onto the global semiconductor market, and the coordination activities undertaken by MITI were thought to have played an important role. The relative decline of the semiconductor industry in the U.S., in turn, spurred the formation of SEMATECH, a consortium that was started by U.S. semiconductor companies, with the help of a subsidy from the U.S. government, to coordinate their research and manufacturing initiatives. A crucial contribution of SEMATECH was the effort to build a consensus roadmap for the industry outlining the critical roadblocks to advancing semiconductor technology. The consensus-building effort for technological advancement was institutionalized in the creation of the International Technology Roadmap for Semiconductors (ITRS), a biennial document released by SEMATECH to this day. In the last decade, as advances in semiconductor technologies brought the industry into the realm of nanotechnology, CNSE has taken the leadership role in coordinating the research and manufacturing activities of the semiconductor firms – so much so that SEMATECH has relocated its entire operation from Austin, Texas to CNSE’s world-class Albany NanoTech Complex.

The lessons from the semiconductor industry have important implications for the development of CIGS thin film solar technology. CIGS technology is expected to expand rapidly in the coming years, with the market research firm Lux predicting a market for CIGS of 2.3 GW by 2015. As CIGS production expands, the need for specialization along the manufacturing supply chain and the subsequent need for coordi-

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nation among the segments of the supply chain will increase. The pressure for reducing costs and improving efficiency will give an incentive for firms specializing in materials and production of manufacturing tools to emerge. Some companies like Manz Automation and Singulus are already producing specialized deposition tools for CIGS manufacturing. Efficient coordination across the supply chain will become important as consumers and firms both learn from deployment of CIGS modules, and as new markets for CIGS emerge.

The ability of CIGS modules to be deployed on flexible substrates holds enormous potential for use of CIGS in BIPV and other similar segments. As costs come down and efficiency improves, CIGS would expand into new market segments involving "plug-and-play" deployment of solar. As CIGS technology expands to these markets, CIGS module manufacturers will need to make new innovations to respond to the demands of consumers in these segments. This might require changes in materials and manufacturing tools. A well-coordinated supply chain is almost a necessity for the CIGS industry to be able to respond quickly to consumer signals, and penetrate these new market segments effectively. PVMC, headquartered at the College of Nanoscale Science and Engineering and spearheaded by CNSE in partnership with SEMATECH, is well placed to play this role of coordinating the different specialized firms along the CIGS supply chain.

CIGS has been demonstrated to be the highest-energy-producing and most likely successful "thin film" solar technology. It offers the greatest potential for lowest cost of ownership (COO) with highest-efficiency, optimal form factor on both rigid and flexible substrates, and it is environmentally safe. As a result of these attributes, it is the fastest-growing solar technology (96 percent CAGR supply market forecast), with potential use for building integrated devices, solar farms, commercial and residential rooftops, portable devices and, potentially, terawatt-scale deployment. CIGS offers the highest probability of U.S. solar industry leadership, with U.S. suppliers representing more than 40 percent of global CIGS manufacturers. U.S. strength in CIGS manufacturing is due largely to U.S. industry's historical leadership in semiconductor technical know-how, capabilities and experience.

While CIGS has inherent advantages of flexible form factor (see examples of tools in Figures 3 and 4) and lower-cost substrates, its market penetration is limited by volume-manufactured module efficiencies around 12 percent (despite laboratory efficiencies demonstrated at 20 percent). The target for CIGS programs is an increase in module efficiency by 50 percent over the next five years, and overall reductions in manufacturing cost structure. Process technology for thin-

Figure 3 – Large-scale Sputtering Tool Capable of Processing 1 m Wide Web to be Installed at USPVMC Manufacturing Development Facility

Figure 4 – Large-scale CIGS Deposition Tool Capable of Processing 1 m Wide Web to be Installed at USPVMC Manufacturing Development Facility

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film CIGS solar cells has reached maturity for mass production. Several companies have begun large-scale production, but further improvement in cell and module performance is needed to reduce costs and improve competitiveness in the PV market. CIGS flexible solar cells have the potential for reduced production costs. However, significant challenges remain that will be addressed through the PVMC to accelerate deployment of CIGS products that have achieved the following cost and performance targets.

To achieve these CIGS solar cell cost and performance objectives, among other challenges, USPVMC will focus on the following high-priority technical opportunities:

(1) *CIGS Cell and Module Structures Process and Equipment Optimization* – optimize manufacturing processes and equipment to close the efficiency gap between lab production and commercial production of high-efficiency CIGS cells.

(2) *Develop CIGS Manufacturing Processes and Metrology for Next-Generation High-Efficiency, High-Volume Production Lines* – develop materials integration, process and equipment to raise efficiencies and commercialize technologies needed for next-generation CIGS manufacturing.

(3) *Develop Methodology for CIGS Reliability Enhancement* – Characterize CIGS materials and process integration interactions to develop specific models around failure mechanisms, performance and yield to provide direction for process, equipment, metrology and innovations.

(4) *Balance of System* – develop BOS technologies that reduce cost and improve the performance, reliability and functionality of CIGS PV systems.

(5) *CIGS PV Manufacturing Productivity* – implement productivity approaches and develop factory systems in a manufacturing development facility to develop solar fabs of the future.

The value proposition offered by PVMC is multifaceted. PVMC – in partnership with industry, universities and government – will harness the interdisciplinary capabilities required to rapidly develop and deploy breakthrough solar technologies, as opposed to making incremental progress. PVMC will offer the capacity for developing “integrated solutions” by bridging new cell, module and materials development. This will lead to improved efficiencies and accelerated availability of new products which, in turn, will enhance productivity and competitiveness for PVMC’s PV industry participants. PVMC will serve as the hub around which an innovation ecosystem for PV technologies will attract, coalesce and grow: research and pre-competitive technology development, commercialization and manufacturing; venture capital and private equity funding; private, public and international investment; the relocation of emerging technology companies and top talent; and increased employment in the participating regions. By integrating the industrial research consortium and manufacturing development facilities models, PVMC offers lab-to-fab capabilities that will support rapid commercialization of new technologies and incubation of new start-up firms. PVMC offers the federal government an unparalleled opportunity to promote the competitiveness of the U.S. photovoltaic industry, recapture lost market share, and retain and create millions of jobs in the U.S. ■

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Eelco Bergman

VP of Business Development; Cyrium Technologies Inc.

As a result of the significant manufacturing overcapacity in the industry, PV pricing has dropped dramatically over the past six to 12 months. The current pricing environment has put intense pressure on all PV systems suppliers to find ways to aggressively drive out cost in their existing manufacturing supply chains and develop novel solutions that will enable further, and more revolutionary, reductions in the LCOE (levelized cost of energy – annualized cost/kwh) of their systems. One approach that is seeing increased adoption is the use of concentration (low, medium and high) both for standard crystalline silicon as well as III-V multi-junction solar cells. The use of concentration provides system manufacturers the ability to extract more power out of their cells, which represent a significant portion of their cost.

In the previous edition of Future Photovoltaics (vol. 7), Solaris Synergy introduced its floating PV system, specifically developed to enable the use of low-cost crystalline silicon solar cells under medium concentration. The floating approach taken by Solaris Synergy offered a solution to the need to cool the PV cells in order to minimize conversion losses typically associated with the high operating temperatures resulting from concentration. In parallel, their design provided a number of installation-related benefits.

In this edition, Solaris Synergy reports on the deployment of their first "multi-module" (15 kWp) floating platform in southern Israel, the module improvements made as a result of the process and the lessons learned. For the balance of the year, the company will focus its attention on the preparations for its next project, a 200 kWp grid-connected system, scheduled for commissioning in early 2013.

Floating Concentrated Photovoltaics: Part 2

Yossi Fisher, Yuri Kokotov, Elyakim Kassel
Solaris Synergy

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Abstract

Solaris Synergy has scaled up its floating concentrated photovoltaic system from a single module to a multi-module floating platform. Within the framework of this project, a pre-commercial 48-module system with an output power of 15 kWp was designed and successfully implemented in field conditions. The company is currently working toward the manufacture and assembly of a demonstration pilot of 200 kW that will be connected to the electric grid.

Introduction

The floating concentrated photovoltaic system was described in the first part of this article, which appeared in vol. 7 of Future Photovoltaics. Its main components are cylindrical mirror-based concentrating optics, silicon PV cells, an evaporation/condensation cooling system, a rotating floatation platform and affixed frame. This part shows the process of scaling up from a one-module prototype, as installed at the "Capital Nature" solar test field in Kibbutz Ketura in southern Israel, to a multi-module floating platform, installed on the "Tekumah" reservoir belonging to Mekorot, the Israel water company.

Since the system is fully modular, the main efforts related to the scaling deal with the floating platform, the fixed frame and the sun-tracking mechanism. However, having said this, while transferring the technology from the one-module prototype of Ketura to the multi-module platform of Tekumah, a number of improvements were also added to the module design. The main goal of these design improvements was to improve manufacturability and to increase module efficiency by adding secondary optics in order to harvest more sunlight.

Floating Platform and Sun Tracking

The platform is essentially a beehive structure made of fiberglass with dimensions depending on the size of the system. Each beehive cell is the place where two modules will be eventually placed. The platform is made of fiberglass beams of an inverted U-shape, allowing the placement of blocks of low-density polymer foam underneath. The quantity of foam blocks is computed to provide the

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floating force that compensates for the system weight. The modules are attached to the cells formed by the crisscrossed beams and a fiberglass ring is positioned around the platform. The function of the latter is to allow the attachment of the rotational tracking system.

An hexagonal fixed super-frame, also made of fiberglass beams, is fixed around the outside of the rotation ring and is secured to the shore by cables that are used to prevent drift of the system. The electric current produced is transferred from the fixed frame to shore where the inverter that converts direct current to alternating current is located via cables adapted to a marine environment.

The floating platform is centered in the fixed super-frame, and is free to rotate via the use of cables that encircle the rotation ring (which is rigidly connected to the platform) and a set of pulley wheels fixed to attachment points on the frame evenly distributed over the perimeter. A fourth cable, also encircling the rotation ring, provides the rotational torque and is driven by a motor and a double-winch mechanism located on the fixed frame.

An electronic compass and a controller loaded with an appropriate algorithm provide the azimuthal position of the sun and of the platform, and the controller drives the motor, sending speed and direction inputs to enable the system to track the sun.

Module Improvement

Parallel to working on the system upscaling, an engineering effort was also launched in order to improve module performance. The goal was to increase electrical power output of the system by maximizing the concentration of the available solar insolation onto the photovoltaic cells. This was planned and achieved by improvements to the photovoltaic module, optical modeling and simulation, and an optimized design of "secondary optics."

A preliminary ray-tracing study was performed using commercial software. It turns out that not all rays hit the solar cell. Many reflected rays are out of range of the cells, causing the energy they carry to be lost for electricity production. In the original design, the ray-tracing software determined the amount of missed energy to be 32 percent. This created a strong motivation to add secondary optics to capture part of the missed rays.

As described in the first part of this article, at the heart of the solar module, a hollow aluminum tube is found. The solar cells are attached to the underside of this aluminum tube, facing downward toward the reflective mirrors, the "primary optics." The tube is partially filled with water and is held at sub-atmospheric pressure, allowing the heat extracted from the solar cells to vaporize part of the water, thus cooling down the solar cells. As this aluminum profile is manufactured by extrusion, it was possible to add side "wings" to the profile without incurring additional manufacturing costs. On these side wings, mirrors can be glued. They form the "secondary optics." The side mirrors reflect the solar rays that missed the cells back toward the cells. The remaining design work was to determine the optimal angle for these side wings and the optimal focal length of the new and improved system. This new concept was manufactured and implemented in the Tekuma reservoir installation.

Field Installation

The beams and pontoons were assembled to form a matrix as seen in Figure 1. In each empty cell, two modules were placed. A fiberglass ring was placed around the platform and attached to it. This ring was then connected to cables that transmit the motion from the motor.

After the completion of the rotating platform, the fixed frame was installed. It was constructed of longer beams of the same fiberglass materials supported by the same foam material. They were first lowered onto the water surface with a crane, connected together and then attached around the rotating platform.

The next step was to drop modules into the cells of the matrix. This was done with a crane that lifted the modules that were pre-assembled on the shore of the water reservoir, which then inserted them into a cell, as can be seen in Figure 2. Figure 3 shows the platform with the modules populating the cells.

After this, the aluminum beams holding the PV cells were connected to the cooling system. The air in the beams was evacuated to reduce the pressure to the level where the boiling point of water occurs, around 35°C.

Figure 1 – Assembling the Floating Platform

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Figure 2 – A Crane Positioning 2 Solar Modules Inside a Platform Cell

Figure 3 – View of the Installed Floating CPV System

Sun tracking is performed with a single electrical motor rotating the entire platform. The motor is placed on the fixed frame, and via the appropriate reduction gear, rotates a double winch that pulls the cables attached to the rotating ring. The speed and direction of rotation of the motor is governed by the controller.

Electrical Connection

The modules were connected in parallel providing a constant output voltage. The total output current increases with the number of connected modules. On each module a power box is connected in order to achieve maximum power at the module level. This is to prevent the undesirable situation where a central inverter determines the operating condition for the entire field and performance is determined by the weakest module. This power box also includes galvanic isolation between the DC and AC circuits. It allows filtering out of the leakage instability in the current and the delivery of “clean” AC current into the public utility grid. The inverter itself is installed on the shore.

Lessons Learned

Solaris Synergy showed the ability of system deployment of 48 concentrating photovoltaic modules with an output power of 15 kWp on a water reservoir. System installation and assembly were fairly straightforward. Two types of connections were critical: mechanical and electrical. Both were properly achieved.

Strong emphasis was placed on safety, as water and electricity are sources of potential hazards, both separately and combined.

The water reservoir of Tekuma is located in Northern Negev, which is a desert region. Sand is a major cause of reflection loss for the mirrors. Water of the reservoir was used for cleaning the mirrors without the use of any detergent.

Next Project

During the remainder of 2012, the company plans to implement (within the framework of a tender from the Israeli Ministry of Energy and Water) the knowledge gained from this pilot installation toward the manufacture and assembly of a demonstration pilot of approximately 200 kW, which will be connected to the electric grid. This is scheduled for construction in the second half of 2012, with a goal of commercializing the technology by the beginning of 2013. This commercialization will signal the beginning of the exploitation of the solar-on-water market, which enables the reduction in usage of valuable land resources for solar power production while at the same time allowing the preservation of water quantity and quality. Those important advantages have already drawn significant attention from many countries around the world, where inland water surfaces are abundant and energy needs are growing. This solution is ideally suited to rural agricultural regions that may be remote from the electric grid but have existing irrigation ponds close to the point of use of the electricity. Additionally, the solution is well suited to water reservoirs belonging to utility companies, where the electric grid already exists and grid connection does not require significant additional infrastructure investment. The low cost, simplicity of construction and ease of deploy-

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ment make this technology a viable solution for many users around the world, providing clean, inexpensive renewable energy for all. ■

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Yossi Fisher – *co-founder & CEO, Solaris Synergy, has over 25 years of experience managing technology companies, particularly in the semiconductor industry. He holds an MSc in applied physics from the Hebrew University in Jerusalem, and a BSc in electro-optics from the Jerusalem College of Technology.*

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METROLOGY & FAILURE ANALYSIS

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Data Correlation

Correlating the physical characteristics of a transistor with electrical performance is critical, both for development and for manufacturing at high yield and performance. The same can be said for photovoltaic devices. One example is the strong correlation between high recombination lifetimes in Cu(In, Ga)Se2 solar cells and high efficiency.[1]

Of course, there are many other characteristics that have also been correlated to efficiency. Experience indicates that the specifics of these correlations are process and materials dependent. In that light, the path to continued efficiency improvements requires these correlations be established during research and development, and monitored during manufacturing. The automated measurement and analysis of physical characteristics for monitoring manufacturing is challenging, and obtaining uniformity across the cell is complicated by the substrate. Articles on these correlations are a useful addition to Future Photovoltaics, and hopefully we will see more of these in upcoming editions.

Two articles are included in this issue's Metrology & Failure Analysis section of Future Photovoltaics. Horner and Hudson discuss a new method that measures full-spectrum, external quantum efficiency. Findlay et al. discuss the connection between unified lifetime metrology and solar efficiency.

1. W.K. Metzker et al., Appl. Phys. Lett. 93, 022110 (2008).

FlashQE Provides 1000x Speed Advantage for In-line Monitoring

Greg Horner, Jamie Hudson
Tau Science Corporation

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Abstract

Flash Quantum Efficiency (FlashQE®) is a new solar cell metrology technique that measures the full-spectrum external quantum efficiency, reflectance, internal quantum efficiency and short circuit current in one second.[1,2] The method uses a unique full-spectrum light engine to measure, in real time, the cell performance as a function of wavelength. Mapping throughput of >2400 sites per hour is possible on cells and modules, with a signal-to-noise ratio that is significantly higher than conventional QE.

Background

Quantum efficiency (QE) measurements are used in laboratories to study the performance of both single-junction and multi-junction cells. QE measures the cell efficiency (expressed as electrons collected per incident photon) as a function of incident wavelength. Traditionally, a QE system light source is built from either a halogen or xenon lamp, a mechanical chopper and a monochromator or filter wheel to isolate the desired wavelength. The technique has existed in this form for decades, but is constrained by the relatively noisy, low-etendue lamps as well as by the serial nature of the data acquisition; in these systems, one wavelength is measured at a time. For these reasons, conventional QE typically takes 5-10 minutes per spectrum, and thus has not been used for high-throughput applications such as spatial scanning or real-time process control.

The technology for FlashQE was developed at the National Renewable Energy Laboratory and was first published in 2008 by Young et al.[1] The motivation was simple: Researchers were frustrated by the slow turnaround and poor stability of conventional QE techniques, and needed something that would allow them to spend more time on cell development, rather than cell characterization.

The group realized that a separate, burgeoning industry might hold the key: LED manufacturers were introducing new colors each month, and they spanned the visible and near-infrared spectrum. This, combined with the concepts of simultaneous modulation, real-time Fourier analysis and a variety of hardware details, led to the first prototype and IP. In 2011, the first commercial systems were delivered to industry, and Tau Science and NREL received a joint R&D100 award for the product.

QE Applications

QE spectra are rich with device information and can be used with appropriate models to extract:

- Front-surface recombination velocity
- Emitter diffusion length
- Bulk diffusion length
- Back-surface recombination velocity
- Band gap
- Short circuit current, via integration

As device complexity increases, additional parameters may be extracted from the unique spectral response of each layer. Examples include:

- CdS thickness
- ZnO or ZnO-Al, as well as the %Al composition
- Band gap of the device, e.g., for amorphous, ternary or quaternary systems that change as a function of deposition conditions (a-Si, CIGS, III-V's)

In addition, QE curves can be used to identify the current-limiting junction in a multi-junction device – something that is of interest for all series-connected devices.

Apparatus

A Tau Science FlashQE system with 64 independently modulated LEDs was used for this study. A lens system is used to focus the beam into an appropriate area – a millimeter-scale spot for scanning applications or 156 mm beam for single-shot, full cell measurements.

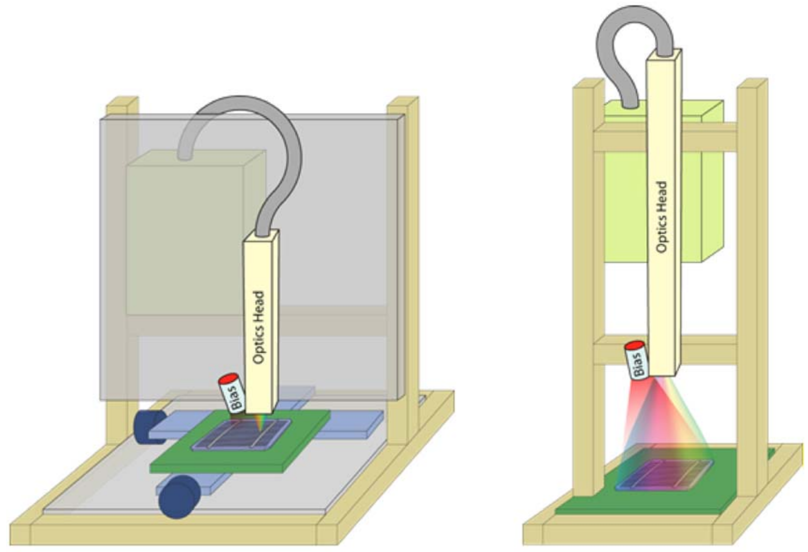

Figure 1 – Configurations of FlashQE system; (left): small spot cell scanner; (right): full wafer inline monitor

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The system simultaneously measures full-spectrum External QE (EQE[λ]) and Reflectance (R[λ]), and from these calculates internal QE (IQE[λ]) and J_{SC}. The measurement time is ~1 second when the system is configured for research work that requires high signal-to-noise ratio (SNR = 500-5000),[2] but this can be adjusted to improve measurement speed at the expense of SNR. In scanning mode,[3] the sample is moved to a new position between each flash, with a typical move time of 0.15 seconds. The resulting multi-dimensional dataset (EQE, IQE and R versus both wavelength and x,y location) is viewed using custom software.

Polysilicon

Silicon manufacturing lines have immediate access to cell-by-cell performance metrics such as efficiency, current output, series and shunt resistance. However, they have not historically had access to spatially resolved full spectrum quantum efficiency data, even in a laboratory setting. There is, however, interest in the topic, since common performance-limiting problems can be detected when spatial maps are available. In this example, we use FlashQE to detect problems in emitter conversion efficiency as well as deep in the bulk. Although the examples use silicon cells, the technique works well on any PV technology.

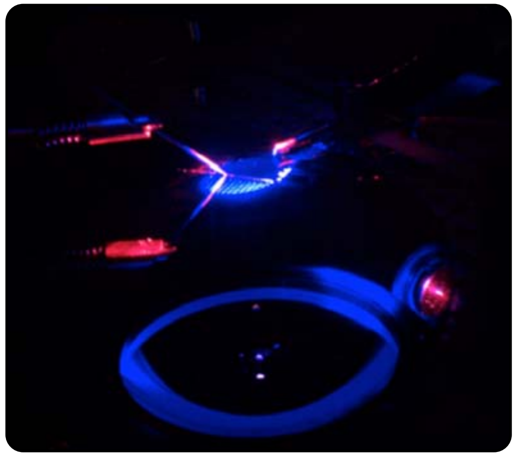

Figure 2 – Small Spot FlashQE Measuring Triple-Junction Cell With Simultaneous Blue and Red DC Bias Lights

A 156 x 156 mm polysilicon cell was scanned with FlashQE at 5 mm steps, and Figure 3 displays the J_{SC} map (left), as well as three EQE maps that span the responsive range of the cell (385-1050 nm). The three busbars are evident in each map, and the scales are indicated in the caption.

The J_{SC} image in Figure 3 is quite unique. J_{SC} can be calculated only when a full-spectrum EQE curve is available, and FlashQE is the only system presently capable of doing this measurement in real time. J_{SC} provides a convenient way to view the entire set of EQE results folded into a single map. To calculate J_{SC}, each EQE is multiplied by the corresponding AM 1.5 (or other) solar spectrum, and integrated over all wavelengths. The result is naturally weighted toward the wavelengths that matter most, allowing a rapid screen of cell performance.

In this case, the J_{SC} map shows a variety of defective regions. The label "A" highlights two isolated defects, and "B" draws attention to a sub-par region adjacent to a busbar. The grains of the poly-Si can be seen in the background, with better-performing grains colored bright yellow.

After observing, via the J_{SC} map, that there are significant non-uniformities in the cell, it is useful to identify the depth at which the problem originates. The second image (EQE @ 385 nm) uses light that penetrates only ~0.1 micron into silicon, and the short emitter diffusion length prevents us from querying deeper. The map shows a weak EQE gradient, but this does not correlate to the major features of the J_{SC} map.

The third image (EQE @ 735 nm) probes approximately 6 microns deep and begins to show grain structure, though there is little correlation to the principal defect seen in J_{SC}.

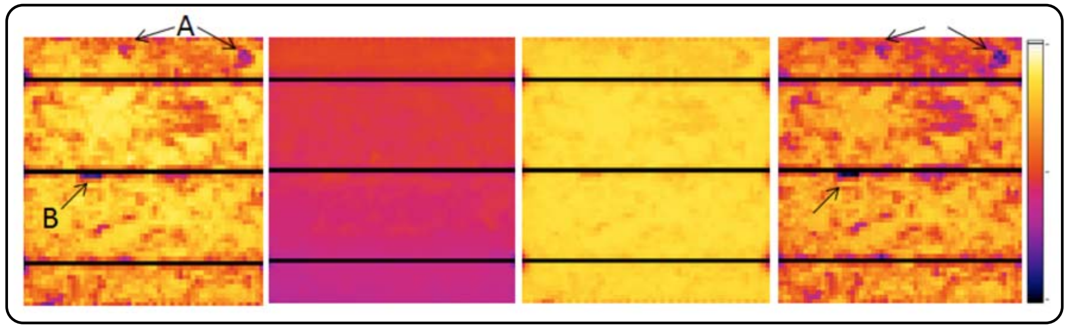

Figure 3 – Maps of (left to right): J_{SC}, EQE @ 385 nm, EQE @ 735 nm and EQE @ 1050 nm on poly-Si. Corresponding min-max scales are 30.5-35.5 mA/cm^2, 30-60%, 65-95%, 30-60%.

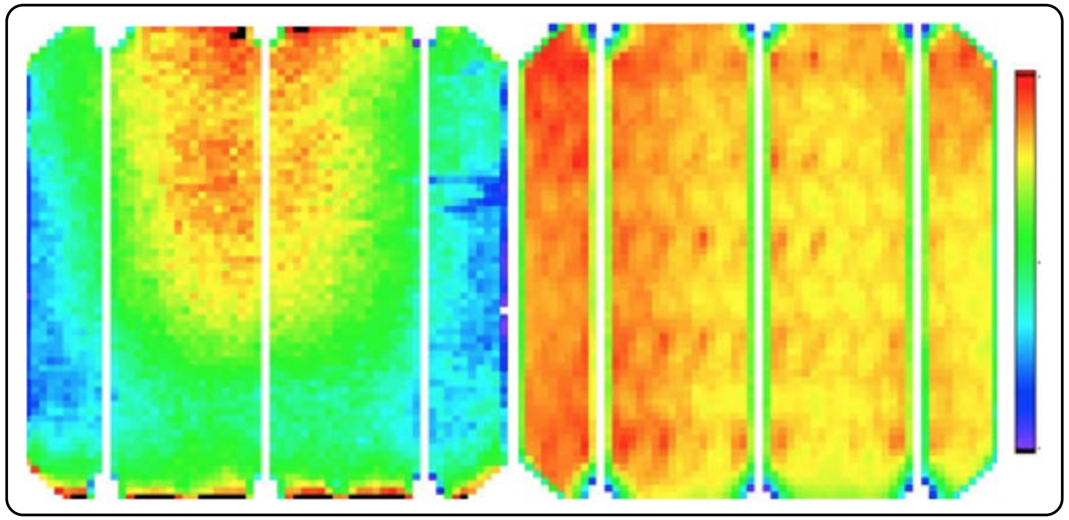

Figure 4 – sc-Silicon EQE maps at 395 nm (left) and 1070 nm (right). Corresponding min-max scales are 36-54% and 29-54%. These spatial variations in emitter and base conversion efficiency are dramatic, and process engineers can use the information to improve baseline performance.

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The fourth image (EQE @ 1050 nm) uses light that reaches the back surface of the cell, and shows all of the major features of the J_{SC} map; in this particular case, the performance-limiting defects are all in the base of the cell.

Single-Crystal Silicon

For comparison, EQE results from single-crystal silicon are shown in Figure 4 at both 395 nm (left) and 1070 nm (right). The dominant uniformity problems are quite different in this case: a U-shaped diffusion boat profile is recognizable in the UV, creating a 10 percentage point EQE gradient directly attributable to emitter performance, while a furnace-firing belt pattern appears to control the long-wavelength conversion efficiency with a more modest five-point swing.

Summary

We have described a new technique that can be configured for R&D scanning applications (either cells or modules) or can be used to monitor each cell in a modern manufacturing plant running 3,000 wafers per hour. The first commercial systems have been used to investigate both conventional and thin film devices, and the primary advantages vis-à-vis traditional techniques include: 1) exceptional long-term stability and signal to noise ratio; 2) light source longevity; and 3) ~1000x speed improvement.

In-line applications include advanced process control for modern cell lines, spectral cell sorting to improve module energy output, and elimination of spectral mismatch correction errors in cell sorters.

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Unified Lifetime Metrology and Impact on Solar Cell Efficiency

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Semilab SDI LLC

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Abstract

Unified lifetime metrology utilizes the quality of decay control technique enabling parameter-free, self-consistent determination of the two lifetimes most frequently used in silicon solar cell manufacturing: the excess carrier decay lifetime, $\tau_{eff.d}$; and the quasi-steady-state effective lifetime, τ_{eff}. This technique opens new possibilities for parameter-free monitoring and wafer mapping of the factors controlling cell efficiency. Mapping of passivated wafers discloses the common presence of "weak spots" in PV cells due to passivation defects such as areas with high emitter saturation current J_0, high surface recombination, and field-effect degradation spots. Elimination of the weak PV spots will benefit the cell efficiency and manufacturing yield.

1. Introduction

After a period of rapid growth of silicon photovoltaics promoted largely by government policies, it is now recognized that future growth depends on increasing the cost-competitiveness of PV electricity. Toward that goal, emphasis is placed on increasing solar cell efficiency. As demonstrated in lab-type solar cells, higher efficiency can be realized in a cost-effective way using advanced stacked dielectric passivation films deposited with new high-throughput technologies.[1] The corresponding passivation engineering is a complex process requiring low interface trap density and strong field-effect, both of which are critically sensitive not only to film deposition process, but also pre-deposition steps and post-deposition firing. Understanding and optimization of new advanced passivation technologies requires advancement of silicon PV metrology used for characterization of passivation.

In this paper, we discuss recent progress in this area that has been achieved using novel lifetime based metrology;[2] namely, the quasi-steady-state microwave-detected photoconductance decay technique, QSS-µPCD, with the quality of decay control, QDC.[3]

An important step is a version of small-perturbation light bias µPCD. The effective decay lifetime, $\tau_{eff.d}$, is measured for laser-pulse-induced excess carrier density, Δn, that is a small perturbation with respect to the steady-state background excess carrier concentration, n_0, produced by light bias. Following Basore and Hansen,[4] we refer to $\tau_{eff.d}$ measured under strictly a mono-exponential condition as the "small perturbation lifetime."

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The term "differential lifetime" is also used in literature in reference to PCD measurement with bias light.[5,6]

The initial version of QSS-μPCD was limited to a low steady illumination range, up to about 2 suns. The present approach is a further step toward unification of lifetime measurement for silicon PV, extending the QSS-μPCD range to 25 suns. Moreover, it overcomes problems with corresponding non-exponential photoconductance decay using the novel quality of decay control QDC technique.[3,7] Finally, the unified approach adopts the procedure of Schuurmans et al.[6] to obtain the steady-state effective lifetime from the small-perturbation lifetime. The results are compared with τ_{eff} values measured with Sinton's QSSPC.[8] Finally, advantages of measuring the small-perturbation lifetime for passivation monitoring are realized using the Basore and Hansen procedure for parameter-free direct determination of J_0.

2. Experiments and Discussion

2.1. Quality of Decay Control

The key to unified measurement is overcoming the problem of non-exponential decay caused by wafer- and apparatus-related factors. The present method introduces measurement of the quality of decay using the QD parameter that is obtained as a ratio of the half-life values in a progressing carrier decay. For an ideal exponential decay $QD_1=QD_2...QD_k=1$, QD<1 identifies measurements leading to erroneous underestimation of lifetime caused by progressively faster decay, and QD>1 identifies an overestimation of lifetime caused by a progressively slowing decay.

QD versus steady-state light intensity forms a control chart that is illustrated in Figure 1(a) using data measured on a low J_0 emitter $p^+/n/p^+$ structure. For conventional settings (1 mm laser spot and 2 mm steady light spot), the QDC chart identifies a significant (QD>1) distortion for QSS intensities above 1 sun. This distortion would cause overestimation of the effective lifetime and an order of magnitude underestimation of J_0. Low-intensity distortion QD<1 is also typical for passivated wafers.

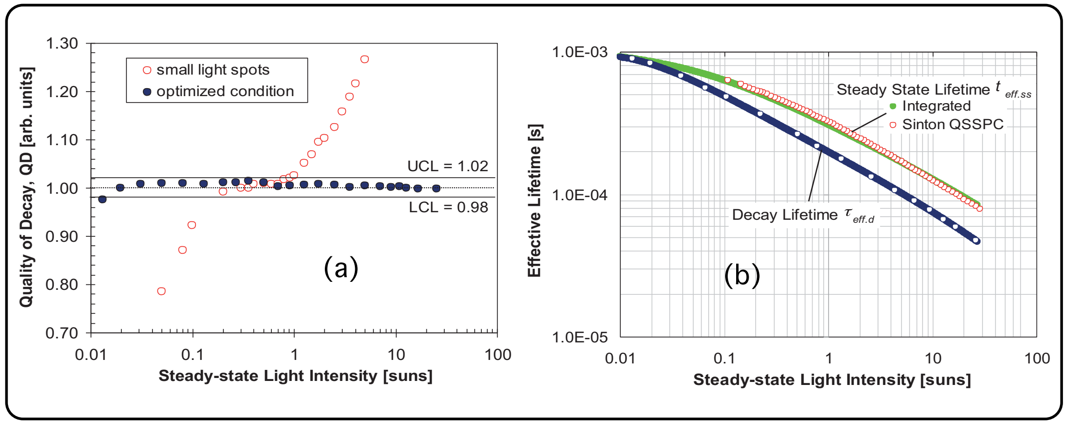

Figure 1 – QSS-uPCD results for $p^+/n/p^+$ emitter test structure: (a) QD control chart for standard and optimized conditions; (b) optimized condition unified lifetime results. Sinton's QSSPC steady-state τ_{eff} is also shown in (b).

These distortions are eliminated by defocusing the pulsed laser beam, increasing the steady light spot size and tuning the microwave frequency. As seen in Figure 1(a), optimization gives QD values within tight specs from 0.98 to 1.02 over a large-bias light intensity range up to 25 suns.

2.2. Measurement of Decay and Unified Steady-State Lifetimes

In unified lifetime metrology, a practically ideal mono-exponential small-perturbation carrier decay is realized with the QDC method. This provides a basis for determination of the steady-state lifetime and the decay lifetime.

As a first step, the measured intensity characteristic of $\tau_{eff.d}$ is fitted with a polynomial expression. The line through the points shown in Figure 1(b) is the fitting curve. The polynomial fit is then used for the integration according to the procedure of Schuurmans et al.[6] that gives "integrated" steady-state τ_{eff}. For a comparison, the τ_{eff} measured with a Sinton QSSPC is also shown in Figure 1(b). Excellent agreement between the two τ_{eff} measurements is apparent, as both lifetimes practically coincide.

The small-perturbation decay lifetime $\tau_{eff.d}$ tends to be shorter than the steady-state lifetime, especially in the high suns range where recombination in the emitter is dominant. Approximately a factor of 2 difference in this range is consistent with Basore-Hansen analytical expressions[4] and also with differential lifetime mod-

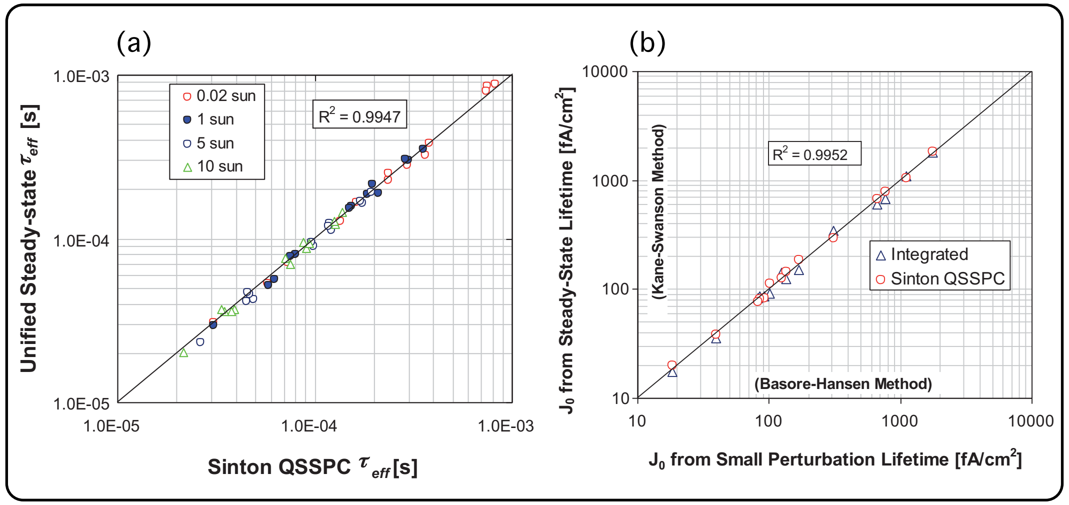

Figure 2 – Comparison with conventional lifetime measurements: (a) steady-state lifetime determined with present unified approach vs. Sinton QSSPC τ_{eff}, (b) emitter saturation current J_0 determined directly from small-perturbation decay-lifetime and J_0 values from the Kane-Swanson method using integrated lifetime and Sinton QSSPC τ_{eff}

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els.[5] In the low suns range, the dependence of lifetime on light intensity becomes weaker, and the difference between $\tau_{eff.d}$ and τ_{eff} diminishes. This is also consistent with theoretical expectations.

Unified lifetime metrology was applied to a series of PV wafers and emitter test structures that were also measured with Sinton QSSPC. Note: Because of measurement spot size difference (Sinton QSSPC 20 x 20 mm and QSS-µPCD variable up to 15 mm diameter), comparative measurements were done on selected wafer sites reasonably uniform, with variations of +/-10 percent within a 20 x 20 mm site.

In Figure 2(a), a correlation is shown between Sinton QSSPC τ_{eff} and the steady-state lifetime obtained with the present unified approach (i.e., by integration of small-perturbation decay lifetime). A 1-to-1 correlation with R^2=0.995 is obtained for a lifetime range covering about two orders of magnitude. This indicates the equivalent character of the two different approaches to steady-state lifetime measurement. 1-to-1 correlation is of importance, as thus far, QSSPC has been treated as a standard for silicon PV. In view of this correlation, one should point out the advantages of the parameter-free nature of the novel QSS-µPCD with QD control measurement. This feature clearly distinguishes the present approach from QSSPC, as the latter requires: 1) absolute photoconductance; 2) excess carrier mobility; and 3) the free carrier generation rate including an

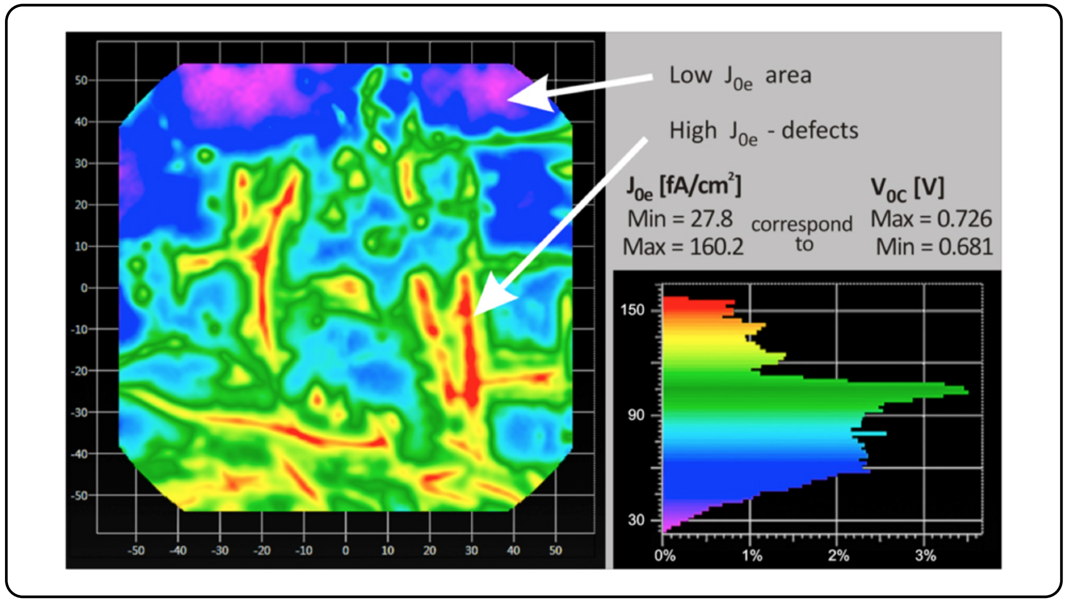

Figure 3 – Example of J_0 Map Obtained With Basore-Hansen $\tau_{eff.d}$ Method Along With Corresponding Open Circuit Voltage

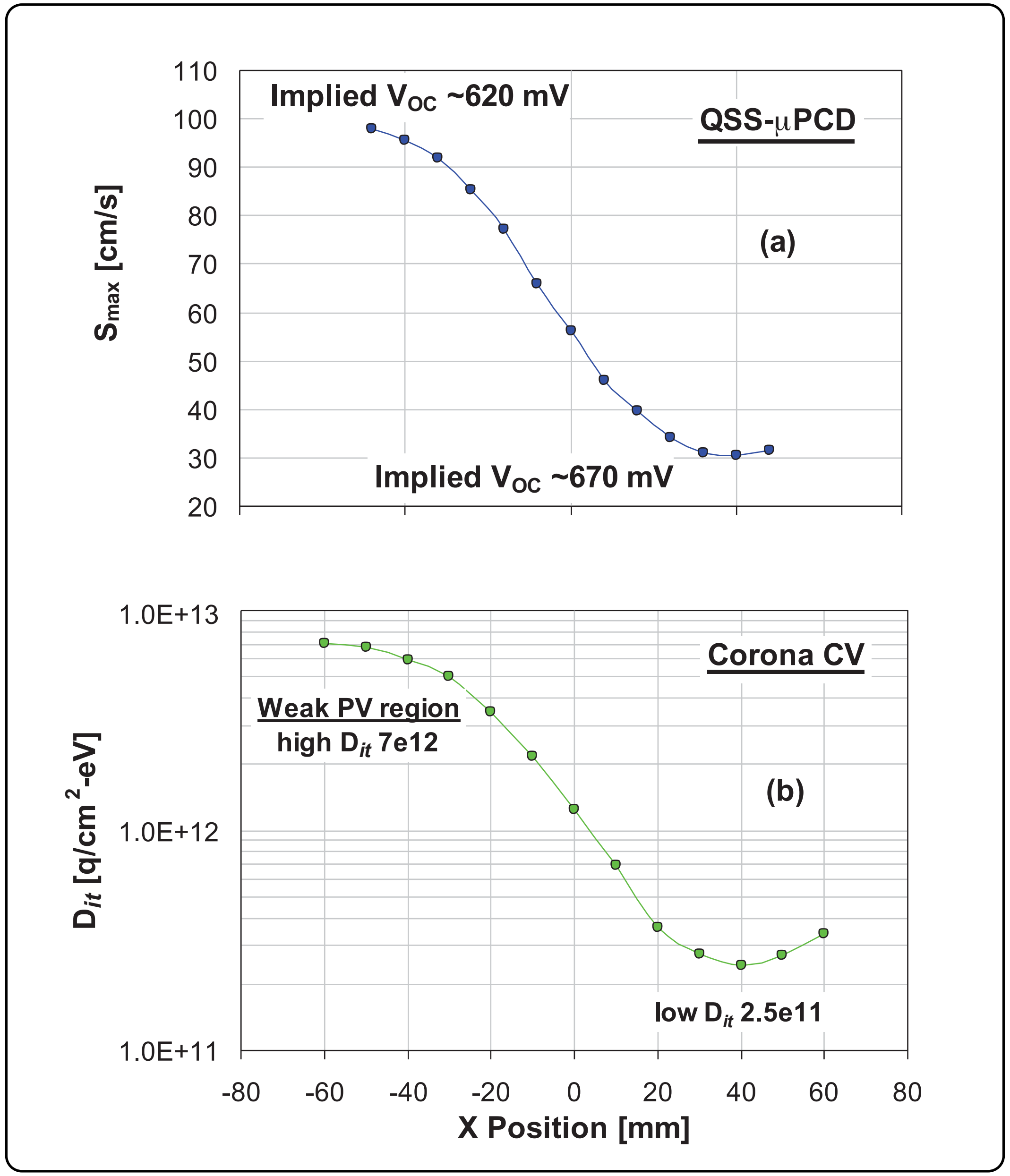

Figure 4 – Defects in SiN_x-based passivation are demonstrated by: (a) high S_{max} (low V_{oc}); and (b) corresponding high and low D_{it}, respectively.

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approximation of carrier profile across the wafer thickness.

2.3. Emitter Saturation Current, J_0

The small-perturbation carrier decay lifetime provides a means for direct determination of the emitter saturation current, J_0, suggested by Basore and Hansen in 1990.[4] Their ingenious but subsequently overlooked procedure does not require any data integration or wafer parameters other than the thickness. In this procedure, J_0 is determined from the slope of ($1/\tau_{eff.d}^2$) versus the generation rate, G. Measurements at two light intensities are sufficient for wafer mapping of J_0.[3]

For a self-consistency test of the unified lifetime method, J_0 can also be determined using the integrated steady-state lifetime τ_{eff} rather than decay lifetime. J_0 calculations are performed with the Kane-Swanson method, i.e., from the slope ($1/\tau_{eff}$) versus the injection level Δn. The injection level is determined as $\Delta n = G \times \tau_{eff}$. Results given in Figure 2(b) show very good 1-to-1 correlation with $R^2 = 0.995$ obtained over two orders of magnitude of J_0. For a comparison, J_0 determined using Sinton QSSPC τ_{eff} with the Kane-Swanson method is also given in Figure 2(b). It is seen that all three J_0 methods produce an excellent 1-to-1 correlation providing additional proof of the reliability of unified lifetime measurements.

2.4. Wafer Mapping and Passivation Defects

In addition to parameter-free measurements, the unified lifetime metrology carries a well-recognized advantage of the µPCD technique; namely, spatially resolved measurement capability, such as wafer scanning or wafer mapping. This capability is available not only for the carrier lifetime, but more importantly for J_0, effective surface recombination (S_{max}) and the injection level, and quite often used implied open circuit voltage (*Implied* V_{OC}). These parameters provide a means for projecting solar cell performance based on measurements at various stages of cell processing.

The new “unified lifetime” technique can be used as a separate metrology unit. However, in this study, we used QSS-µPCD with QD control available in the multi-function Semilab PV-2000A PV metrology platform that enables correlation of different passivation sensitive parameters.[9]

During extensive inspection and metrology of passivated wafers using wafer mapping and scanning, we have found that practically all investigated structures contain passivation defects within following categories:

- high J_0 areas or spots
- high S_{max} area or spots
- high D_{it} area or spots
- area with inferior field-effect passivation

All of these defects can deteriorate cell efficiency.

An illustration of J_0 passivation defects is given in Figure 3. The J_0 map of a $p^+/n/p^+$ emitter test structure shows high J_0 defect areas, with values as high as 160 fA/cm^2. The map also shows regions of low J_0 areas, with values approaching 28

Based on the simplified but often-used single-diode approximation, one can estimate (assuming the typical short circuit current of 38 mA/cm^2) the open circuit voltages in good passivation areas at 726 mV and at only 681 mV in defective areas.

The results in Figure 3 pose an obvious cell efficiency question: How to eliminate passivation defects and to achieve the lowest J_0 over the entire wafer?

The processing parameters that affect J_0 include the sheet resistance and the texturing. However, none of them is expected to vary significantly from site to site. Two other parameters – the interface trap density, D_{it}, and the fixed charge contributing to field-effect passivation – can cause much larger J_0 variations, and they were included above in four categories of passivation defect. These defects are sensitive to the film deposition and to the firing; the origin of defects in Figure 3 may involve contribution of both processes.

The unified lifetime metrology has also been found to be very useful for measurement of the effective surface recombination S_{max}. The results of S_{max} line scanning on mono-crystalline Cz PV wafers with SiN-based stacked passivation dielectrics are presented in the upper part of Figure 4 together with a corresponding line scan of the interface trap density. The latter was measured with the non-contact corona C-V technique available in the same PV-2000A tool.[9] The QSS-µPCD scan of S_{max} identifies a defective passivation area on the left side of the wafer and a good passivation area on the right side of the wafer. The corresponding implied V_{oc} values obtained from the steady-state lifetime indicate 620 mV and 670 mV values for bad and good passivation areas. The D_{it} scan at the lower part of Figure 4 indicates that the inferior passivation corresponds to high D_{it} up to 7e12 q/cm^2-eV, while the good passivation area has about 30 times lower D_{it} in the low e11 q/cm^2-eV range.

Similar to the case of J_0 defects in Figure 3, the results in Figure 4 stimulate an important passivation engineering question: Can passivation steps be optimized to maintain low D_{it} over the entire wafer?

The metrology presented in this paper should help to answer such questions, benefiting cell efficiency and manufacturing yield.

Conclusions

QSS-µPCD with quality-of-decay control facilitates high-precision, parameter-free unified measurement of the carrier decay and the steady-state lifetimes.

The technique opens new possibilities for mapping of PV wafers and emitter passivation structures. The examples illustrate passivation defects manifested as high J_0 or high surface recombination areas. It is believed that the presented metrology will help to improve cell passivation that is important for cost-effective fabrication of higher-efficiency solar cells.

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MODEL & PANEL, TEST & CONSTRUCTION

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Urs Schoop
Chief Technology Officer, Global Solar Energy

In recent months, we have seen module prices driven to historical lows. While this is great for customers and increases the speed of solar installations, it also puts tremendous pressure on the cell and module manufacturers as well as the supply chain. Module makers and material suppliers, to stay competitive, need to accelerate their cost-reduction roadmaps. While effects of process and material changes are easily verified in initial performance, reliability and durability tests have long timelines and are much more costly to perform. If not done thoroughly, the quality of the final product can suffer, sometimes only visible after years in service.

In the following article, researchers from DuPont review the materials their company is offering to the PV industry and the value they add in the current economic environment. New materials such as improved metalized pastes support innovations in the cell design and help advance cell performance and module efficiencies. Existing and proven materials, as, for example, DuPont’s encapsulants and backsheet materials, have advantages in long-term reliability, as they have a proven track record for stability and durability. In general, they make a strong case for increased collaboration between strategic materials suppliers and module manufacturers to decrease development time, but most importantly to maintain high-quality standards for reliable and durable products in a time that is dominated by cost reductions.

Materials Make the Module

Homer Antoniadis
DuPont Photovoltaic Solutions

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It's no secret that efficiency, lifetime and overall system costs for photovoltaic (PV) modules are driven in large part by the materials specified in their production. In fact, advanced materials are more important than ever in helping today's solar cell and module manufacturers differentiate their products with superior power output and longer life performance that deliver increased investment rates of return (IRR) to PV system owners and financiers.

What is less apparent is that under the current climate of increasing cost pressures, module producers – even some of those deemed "bankable" – are considering, and sometimes taking, shortcuts to substitute unproven materials to help manage short-term costs. Poor material selection presents a significant risk not only to module performance, but also to the quality and reputation of module manufacturers. Ultimately, this has the potential to jeopardize the credibility of the entire PV industry at this critical time in its development. PV system developers, insurance companies and investors are beginning to closely scrutinize PV system failures, and educate themselves about the integrity of materials being used inside modules in order to mitigate their investment risk.

Why Materials Matter

The solar business is on track to become a $100 billion industry by 2015. It is in all industry stakeholders' interests to continue to accelerate the growth and momentum of solar energy as a viable element of the world's energy mix. Over the next five years, industry experts anticipate 20 percent average annual growth in installations, as PV reaches grid parity in more and more markets. The solar market still represents a mere 0.4 percent of the total global generation capacity today; however, it represents more than 15 percent of new electrical energy capacity being added on an annual basis. For PV technology to reach its potential, it must prove to be more and more efficient in terms of the amount of sunlight converted into usable electricity, in addition to delivering reliable performance over an expected lifetime of at least 25 years. Any PV system failure, either catastrophic or due to loss of power over time, could undermine solar energy's viability as an economical and reliable energy source.

Careful selection of key materials can mitigate this risk. The three most critical materials used in the production of solar panels include silver metalization pastes, used to efficiently conduct electrical power from solar cells, polyvinyl fluoride backsheets, the outer "skin" that protects the inner elements of a solar panel from damage from the harsh environment on a rooftop- or ground-mounted installation, and encapsulant materials used to protect the cells. All of these materials must be able to deliver the necessary high-performance specifications of a solar panel over 25 years.

Let's take a closer look at how advanced materials can positively impact module efficiency and lifetime.

Enhancing Conversion Efficiency

Metalization pastes have been used in the electronics industry for over 40 years, and leading suppliers continue to make improvements in these critical materials in terms of cost, performance and quality. In the PV industry, silver metalization pastes are used to collect and conduct the electricity generated on the surface of a solar cell. Due to advances in metalization materials technology over time, the amount of sunlight converted into usable electricity (referred to as the conversion efficiency of a solar cell), has dramatically improved, from about 12 percent in 2000 to 19 percent in 2012, thereby delivering significantly more electrical power output from a solar module. Every percentage improvement is significant, as it results in a 5 percent reduction in the cost of the overall solar power generation system. Many leading module makers consider high-efficiency solar cells as a key differentiator in today's competitive market.

Recently, new metalization paste materials have been developed that not only improve efficiency in standard solar

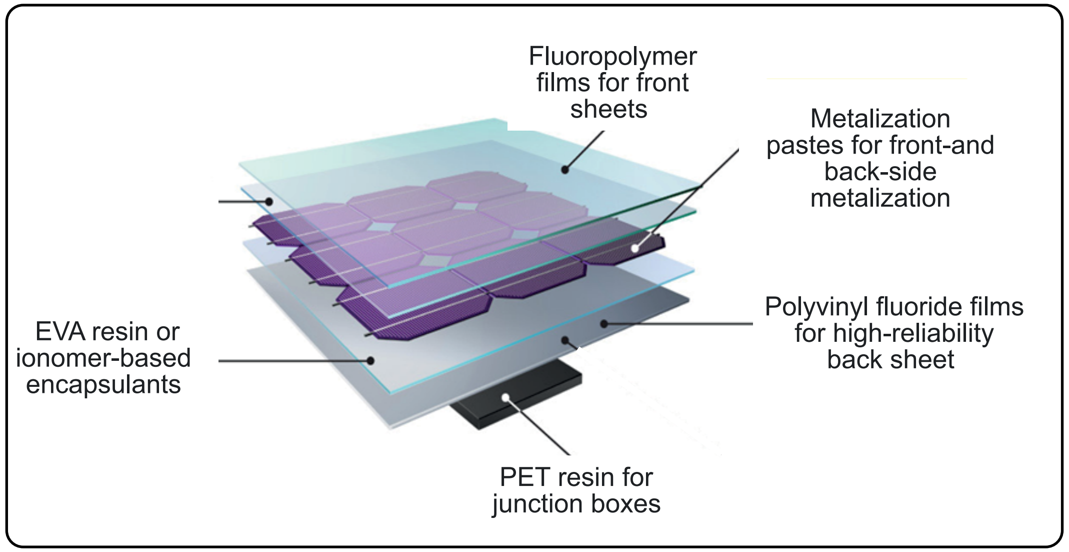

Figure 1 – PV module materials must be carefully selected to ensure reliable power output over a system's 25-year expected lifetime.

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cells, but also enable the production of new types of cell designs capable of delivering even larger step changes in PV conversion efficiency going forward.

For example, DuPont has developed a photovoltaic silver metalization paste called Solamet® PV17 that has become the leading silver paste on the market today, due to its ability to increase solar cell efficiencies by an additional 0.4 percent via its unique ability to enable doping diffusion optimization with lightly doped emitters (LDEs). This integrated material and process technology has opened up new avenues to increase solar cell efficiencies using advanced silver metalization pastes. Prior to PV17 being released to the market, the industry had no commercially available option for making a screen-printed front-side metalization that could economically and practically enable an LDE. The excellent silicon-to-silver contact of PV17 technology has demonstrated a wider range of diffusion optimization and higher cell efficiency.

PV17 technology is now being deployed in solar cell manufacturing sites throughout the world. RWTH-Aachen University recently published a comparative study that found Solamet® PV17 outperformed four competing products, demonstrating its ability to contact 100 ohm/sq., LDE emitters on multicrystalline cells – the first time this had been achieved – with lightly doped phosphorous surface concentration. This enabled an efficiency improvement of a full 1 percent.

DuPont is also producing metalization pastes that reduce dependence on silver metals and thereby reduce costs for manufacturers, without compromising solar cell efficiency.

But efficiency advantages gained through the use of advanced metalization pastes are quickly lost if the module structure is not properly protected. Long-term protection for the sensitive components in the module is primarily the role of two key components: PV encapsulants; and the outer-skin, PV backsheet.

Extending Module Lifetime

From an investor's perspective, the cost of a PV system can be reduced significantly when the system can run efficiently and effectively for a longer period of time, making PV a more attractive investment based on the levelized cost of energy (LCOE), compared to alternatives. For example, investment returns can increase by over 40 percent over the life of the system if the lifetime of the PV system can be increased by 10 years.

Module lifetime can be broken down into three areas of importance: reliability; durability; and safety. All of these are vital in delivering the expected IRR for solar projects. Reliability means no early-onset catastrophic failure; durability means minimal annual power degradation; and safety means no injury to people or damage to physical assets.

From the earliest days of PV manufacturing, clear, soft, shock-absorbing ethylene vinyl acetate (EVA) resins were found to make ideal encapsulants. Converted into sheets that surround and protect solar cells and module circuitry, EVA resins have been shown to deliver decades of reliable service. However, EVA is susceptible to degradation in external environments, making it essential that the formulated sheet contain a robust stabilization package. Unfortunately, lab tests of EVA encapsulant stability do not reflect real-life conditions, and as the number of EVA resin and sheet suppliers has multiplied, EVA discoloration, embrittlement or acid generation is increasingly observed. While it is tempting to consider all types of EVA equivalent to one another, and make selections solely based on cost, experience has shown this to be a dangerous approach – especially as cells get more efficient and sensitivity to environment (e.g., acid, moisture) increases.

More recently, ionomer-based encapsulants, leveraging their intrinsic UV stability in addition to well-demonstrated properties of clarity, strength, stiffness, flow and adhesion are delivering not only long-term protection of PV cells, but also improved design, productivity and cost advantages. While slightly more expensive than EVA, ionomer has almost two decades of field use as an encapsulant, and these modules have demonstrated exceptional results in both reliability (elimination of PID) and durability.

However, by far, the largest surface area barrier protecting a solar module is the PV backsheet, and its performance is paramount. Its purpose is to protect the sensitive module components from the harsh external environment while providing electrical insulation for the expected lifetime of the module. Premature backsheet failure can result in significant power loss and investment loss.

Many PV backsheet materials are relatively new to the market, and have not been proven to reach the expected 25-

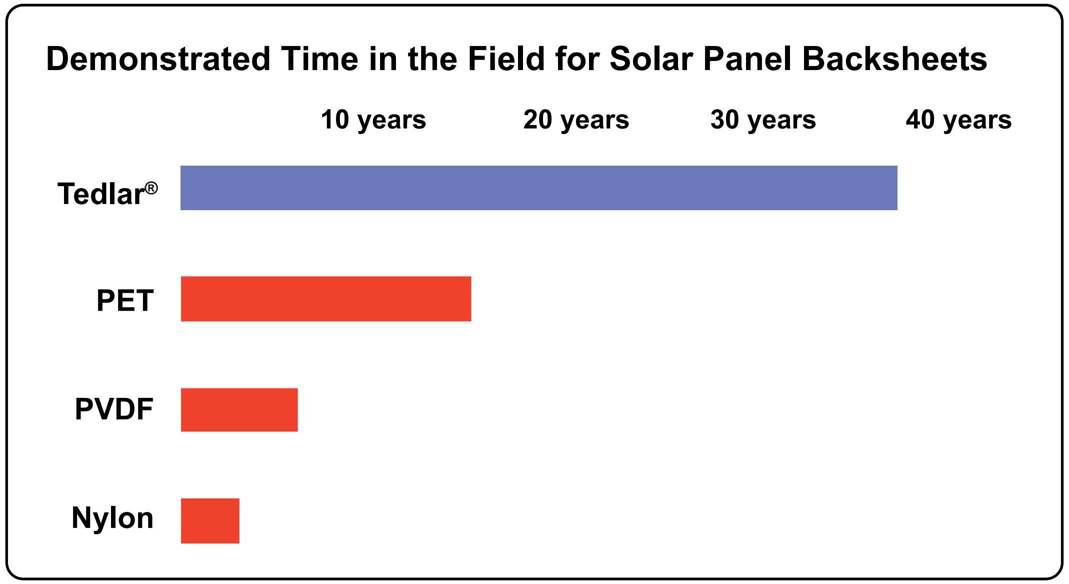

Figure 2 – Only 1 PV backsheet material has been proven to protect solar modules for over a 25-year lifetime.

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year module lifetime. Examples include polyethylene terephthalate (PET), which has been around for about 15 years; polyvinylidene difluoride (PVDF), which has been in use for less than 10 years; and nylon, which has been in use for about five years. They have typically been sold on the basis of accelerated aging tests, which we are learning now cannot accurately predict lifetime performance.

Long-term outdoor exposure, specifically in PV applications, is the ultimate test for all module components, material quality and manufacturing quality. To date, PV backsheets made with DuPont™ Tedlar® polyvinyl fluoride (PVF) film remain the industry standard for reliability, as it is the only known backsheet with over 25 years of field proven lifetime. PV module backsheets made with Tedlar® provide critical, long-life protection to the module, safeguarding the system and enabling long-term PV system returns. Tedlar® and other DuPont materials have been time-tested in over 5 trillion panel-hours of outdoor PV field installations across the globe since 1975.

Recently, the industry is beginning to see far more failures due to other lesser-performing and unproven materials that have been introduced in the past five years and have been in the field long enough to show failures.

PV Profitability

Profit margins in several parts of the PV value chain have declined significantly over the last few years. Cell and module manufacturers have experienced significant margin pressure due to overcapacity and declining solar market incentives. Many manufacturers have declared, or are very close to bankruptcy. One industry source suggests that of the 256 module makers operating in 2011, we can expect to see fewer than 50 survive by 2016.

Prices for cells and modules have dropped rapidly as a result of overcapacity and overproduction. In 2008, solar modules were priced at $4.00 per watt, and in 2012, prices have dropped to a staggering $0.85 per watt. Hundreds of rapidly growing cell and module manufacturing companies that have sprung up in the last decade face the daunting challenge of reducing costs further and returning to profitability as the industry transitions to grid parity.

The solution – or part of it – lies in substantial increases in cell and module conversion efficiencies. As described above, if cells and modules are not protected by a highly durable backsheet structure that enables a long service life, the efficiency gains are meaningless. Materials *do* matter to help promote and protect PV module performance.

Evidence gathered from recent module failures is suggesting that some module manufacturers have substituted unproven materials in modules as a way to manage their costs and preserve profit margins. In one recent audit of module shipments, measured defect rates rose from 5 percent in September 2011 to nearly 25 percent by February 2012. Awareness is increasing for system owners and investors that unproven materials are having a negative impact and will lead to increased costs.

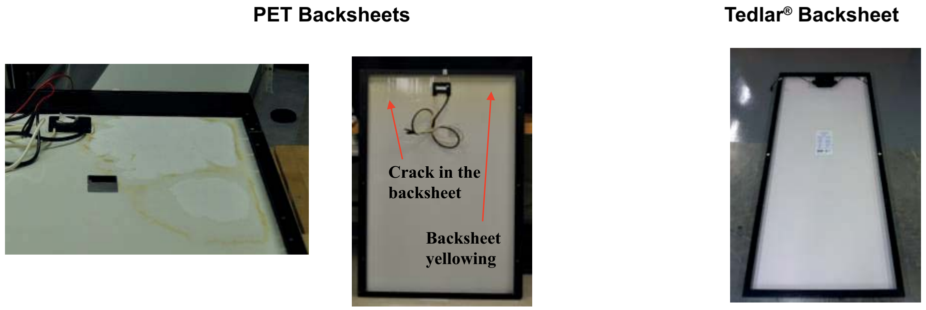
When Modules Fail

The fact is, if a module fails, it is expensive and time-consuming for end-users to replace and reinstall. Before that module fails completely, it is most likely operating at a notably lower efficiency, reducing the system's output and payback. The reason that most modules fail is most likely that the materials used in the manufacturing the installation process were of lower quality, resulting in backsheet failure, glass delamination, backsheet delamination or encapsulant discoloration.

The consequences can often be dire. Faulty modules reduce conversion efficiency and IRRs, but can also damage suppliers' and vendors' reputations and threaten the well-being of their businesses. Widespread module failures have the potential to threaten the continued growth of solar energy.

Awareness among system owners is growing that warranties are an unpredictable means of protecting an investment in a PV system. It can take weeks or months to resolve a warranty claim, assuming a module manufacturer is still in business, and even when a module warranty claim is accepted by the manufacturer, it is possible the exact size and power

Fielded Modules Demonstrate that Materials Matter



	Duration in Service	Nameplate Rating Cell Type	Backsheet	Wet Leakage	IV Measurement % Degradation % Degradation/Year
Module 1	12 Years	143 W mono-Si	PET	Fail	77 W 46% 5%
Module 2	10 Years	125 W poly-Si	PET	Fail	105 W 18% 1.7%
Module 3	11 Years	100 W mono-Si	TPT®	Pass	91 W 9% 0.8%

Figure 3 – PET backsheets were the first 'material experiment' in backsheet, carried out in Japan. They resulted in significantly shorter module lifetimes. Now many additional 'experiments' are playing out in the industry.

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output of a specific module won't be available. Any replacement module almost certainly won't be matched to the existing array in power output or in size, causing performance issues, increased costs and possibly safety hazards upon installation and operation of the replacement panel. There are aesthetic issues when the panels don't match. Typical module warranties only cover the cost of the replacement module. Neither installation costs nor compensation for lost power output for the time period between module failure and replacement are covered. Other indirect costs may include brand damage and increased insurance costs.

Figure 4 – Backsheet failure, glass delamination, backsheet delamination and encapsulant discoloration are all modes of failure possible when unproven materials are used in solar module construction.

Large-scale warranty claims can be expensive. One company recently paid in excess of $250 million to cover warranty expenses tied to the replacement of modules that failed in the field after just three to four years. Few module makers have sufficient financial resources to provide warranty coverage for a failure of this size.

For these reasons, solar system owners are beginning to understand that they are more protected purchasing a system that uses proven design, materials and manufacturing processes so it is less likely to fail.

Strategic Supplier Relationships

Many leading PV module producers have discovered that strategic relationships with leading material suppliers can have long-term benefits. DuPont, for example, is the leading material supplier to the PV industry (ex silicon), and has announced several strategic agreements within the past year focused on material supply and technology collaborations. Those materials can be more readily optimized for highest performance within a specific manufacturing process. When brought to the table early on, suppliers can engineer materials that enable new and improved processes to accelerate manufacturers' progress. New PV metalizations that enable high-efficiency cell architectures such as LDEs are one such example.

Manufacturers are increasingly working in collaboration with material suppliers, relying on them for process expertise and technical support to accelerate their achievement of technical and financial goals.

Compromising quality will not help overcome the current challenges in the PV market. On the contrary, improving efficiency, lifetime and overall system costs will continue to be critical to the success of PV. The world is watching what materials go into modules today. The sustainability of our industry is at stake. ■

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Homer Antoniadis *is the global technical director for DuPont Photovoltaic Solutions, responsible for accelerating the introduction of next-generation DuPont materials into the solar energy market. He joined DuPont in 2011 with the acquisition of Innovalight Inc., where he held the position of chief technology officer and vice president of engineering. Dr. Antoniadis' 20-year career includes positions with Osram Opto Semiconductors, Hewlett-Packard Labs and Xerox. He earned his Ph.D. and M.S. in physics from Syracuse University and a B.S. in physics from Ioannina University, Greece.*

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