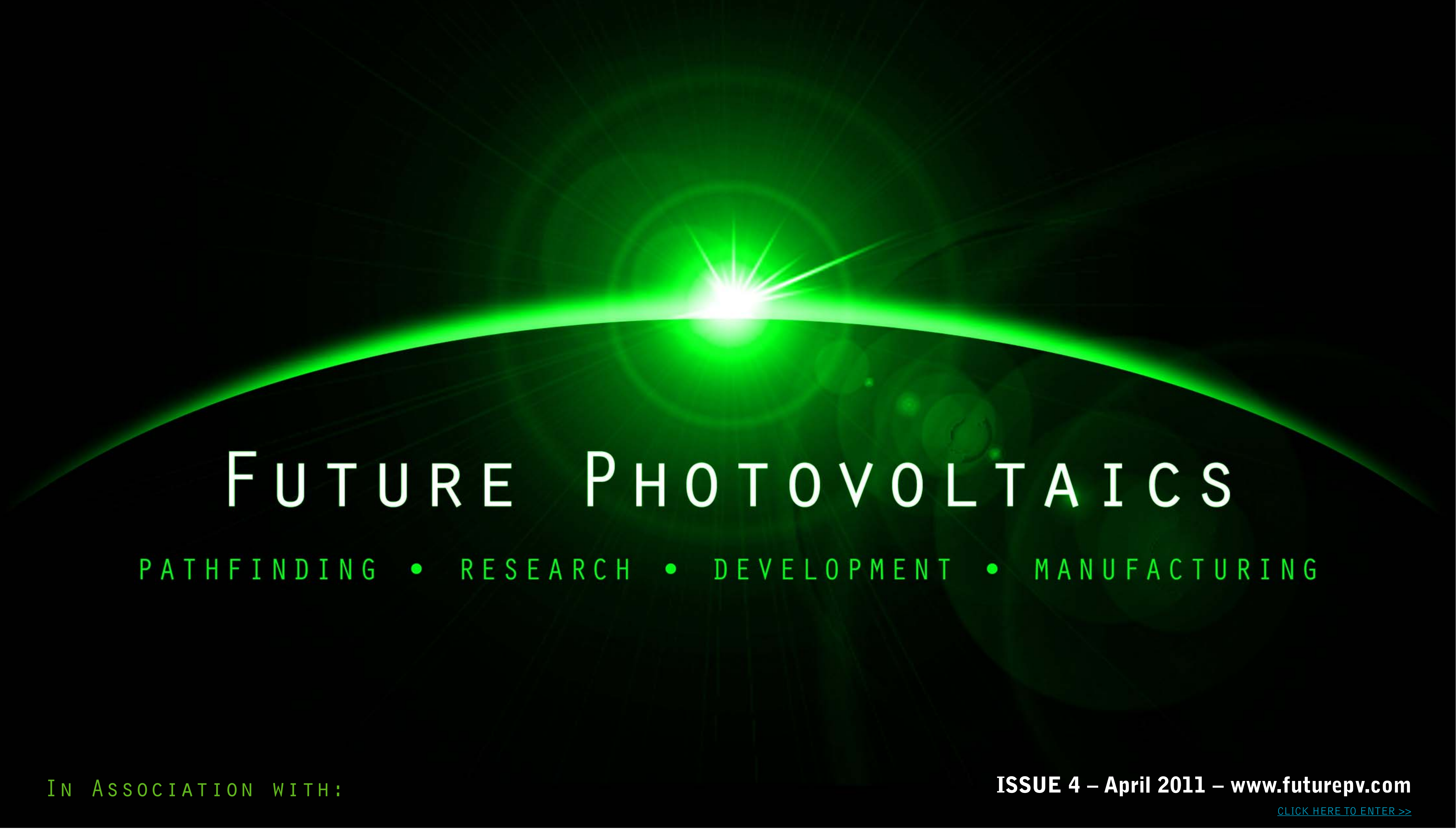

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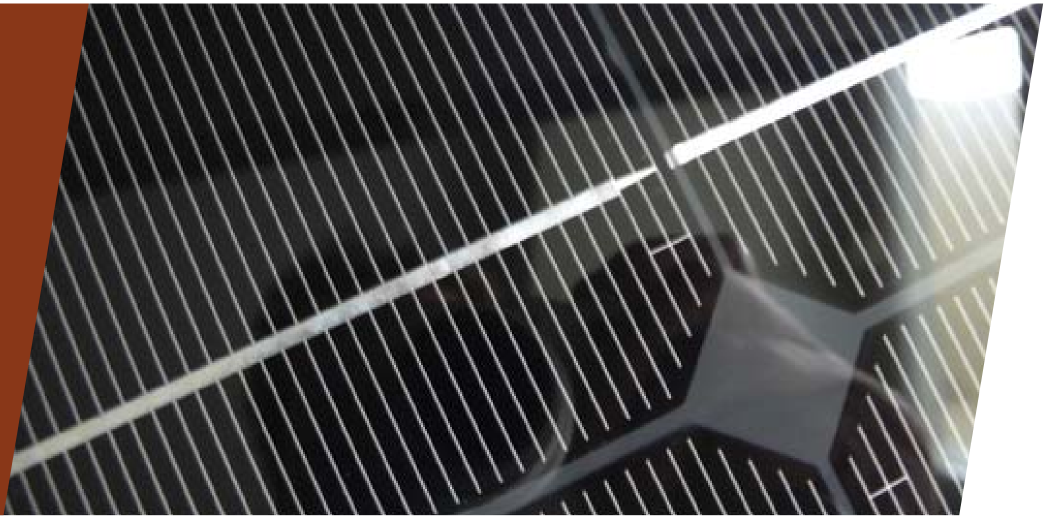

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Welcome…

…to Future Photovoltaics' fourth issue, marking our first full year of issues (FPV is tri-annual). As we're getting increased input and feedback from a readership that's diversifying at a surprising rate (38.6 percent of readers are from China now; welcome!), we're trying to bring new ideas and concepts to you in order to break out of what's been described to us as a "solar farm mentality."

With this in mind, we'd like to highlight the first in a series of articles that bring ground-breaking PV ideas to your attention in the works of Greenlight Planet and Solar Roadways. Both ideas use PV technologies to solve energy issues in very different ways, and serve to highlight the prospect that PV can not only change energy generation, but change it at a societal level. These articles will be followed by submissions from other visionaries; some more well known, others that we hope will inspire your own ideas.

The Future Photovoltaics team

CONTENTS

"The quest to replace fossil-fueled electrical grids…" T. Patrick Walsh - p21

FUTURE VISIONS & CURRENT CONCERNS

NEW TECHNOLOGIES & MATERIALS

SILICON WAFER PHOTOVOLTAICS

<< PREVIOUS PAGE | NEXT PAGE >>

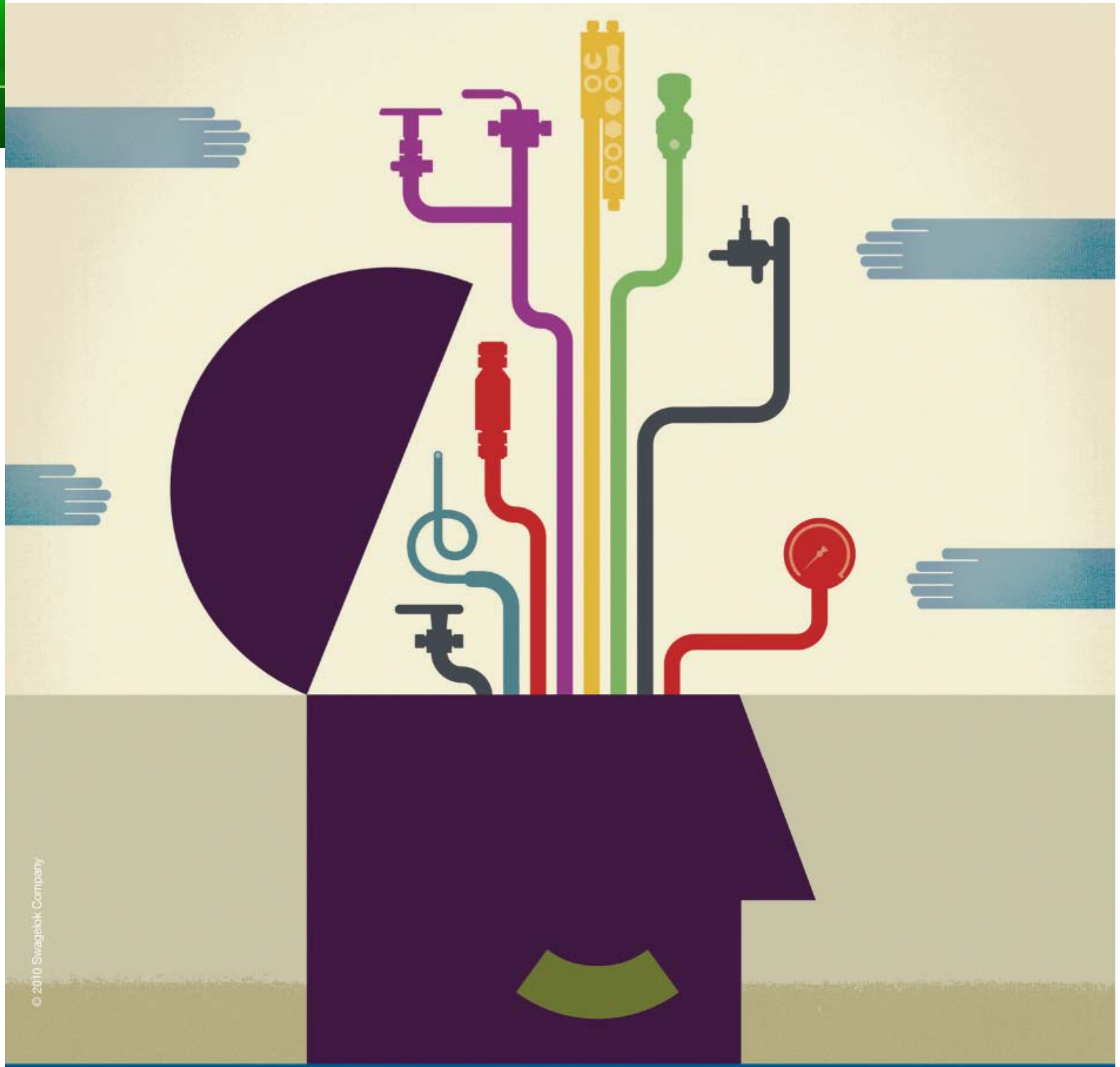
CONTENTS

"The interest in harnessing the sun for energy…" Louay Eldada - p40

THIN FILM PHOTOVOLTAICS

MANUFACTURING EQUIPMENT & MATERIALS

<< PREVIOUS PAGE | NEXT PAGE >>



CONTENTS

“The goal for production is to maximize equipment uptime...” Jean Randhahn - p61

METROLOGY, TEST & FAILURE ANALYSIS

MODULE & PANEL CONSTRUCTION

PHOTOVOLTAIC SYSTEMS

EDITORIAL PANEL

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

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.

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. Christoph has authored and co-authored more than 150 papers and holds 200 patents and patent applications.

Torsten Brammer

Torsten Brammer, photovoltaics research consultant

Torsten Brammer has focused on photovoltaics since 1993. He graduated from the University of Karlsruhe (Germany) and the Australian National University, Canberra (Australia). After his degree, he joined a solar company in Ghana (West Africa). At the Research Center Jülich (Germany), he did his dissertation on thin film PV. In 2004, he joined Q-Cells SE, where he was responsible for the optimization of the crystalline silicon solar cell production process. In 2006, he became technical managing director of the Q-Cells spin-off Sontor GmbH, which was merged with Sunfilm AG in 2009. At Sontor and Sunfilm (now Schüco TF GmbH), he was responsible for R&D. Since 2011, he has been offering consulting services for technology, product design and business planning. Also since 2011, he has been offering consulting services in the area of metrology systems together with his associate Jörn Suthues.

<< PREVIOUS PAGE | NEXT PAGE >>

EDITORIAL PANEL

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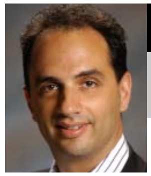
Alain C. Diebold

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 PV 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

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Robert E. Geer is a professor of Nanoscale Science and vice president for Academic Affairs in the CNSE at the University at Albany. He has published more than 100 technical articles, books and book chapters. Professor Geer's 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.

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 graduated with a degree in physics from the University of Karlsruhe, Germany. 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 Freiburg, Germany. Mr. Lerchenmüller was among the initiators of the CPV Consortium, a globally acting industry organization for which he is a member of the board of directors.

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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.

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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.

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Brad Hines is VP of engineering at Idealab, a creator of a number of cleantech, Internet and technology startups. He graduated from the Massachusetts Institute of Technology with a B.S. and M.S. in electrical engineering.

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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 with topics ranging from material development to grid controls. 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 and has given scientific presentations at conferences and symposiums around the world.

<< PREVIOUS PAGE | NEXT PAGE >>

EDITORIAL PANEL

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

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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.

Mike Moore

Vice President, SVTC Solar

Mike Moore is vice president of SVTC Solar, where he is responsible for guiding the company's Solar strategy and overseeing day-to-day operations of the Solar facility. He holds a BSEL from Cal Poly State University, San Luis Obispo, and an MSEE from San Jose State University.

Brent Nelson

Group Manager, Process Development & Integration Lab;
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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.

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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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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.

Christopher Case

Independent Consultant, Solid State Solutions

Christopher Case is currently an independent consultant with Solid State Solutions (UK), serving the photovoltaics, electronics, chemicals and gases industries. He chairs the Interconnect Working Group of the ITRS. At Brown University, Christopher pursued photovoltaics, where he was an assistant professor of engineering and director of the Thin Film Institute. Christopher was a Fulbright-Hays scholar at the Université de Bordeaux and earned a Ph.D. in materials science from Brown University.

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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.

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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.

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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.

<< PREVIOUS PAGE | NEXT PAGE >>

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Prof. dr. Wim C. Sinke is staff member Program & Strategy in the Solar Energy unit of the Energy research Centre of the Netherlands (ECN) and part-time professor at Utrecht University on "Science and Applications of Sustainable Energy Systems." He is an active member of the European Photovoltaic Technology Platform. Sinke has 30 years' experience in photovoltaics. In 1999, he received the Royal Dutch/Shell Prize for Sustainability and Energy for his work in the field of photovoltaic solar energy.

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Robert Vinje is managing director for SunPower's 3rd Cell Manufacturing Facility in Melaka, Malaysia. 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.

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FUTURE VISIONS & CURRENT CONCERNS

Click here to return to Table of Contents PRINT this article E-MAIL this article

Wim C. Sinke

Staff Member Solar Energy
Energy Research Centre of the Netherlands

Where technology and passion meet …

Photovoltaics: from milliwatts to gigawatts with only one building block – the solar cell. From small stand-alone systems for rural use via medium-sized grid-connected, building-integrated systems to large-scale power plants with just one component: the solar module. Examples illustrating two of the major strengths of photovoltaics: modularity and versatility.

This issue of Future Photovoltaics brings us two exciting and, above all, personal stories about very different types of applications. At first sight they have little in common: One is about rural lighting powered by photovoltaics, the other about driving into the future on solar roadways. When reading them, however, I found that they are just two sides of the same coin. Photovoltaics is like a big box of Lego (or K'nex or Meccano or Lincoln Logs or whatever you grew up with). You can do almost anything with it and you will never get bored.

It only takes a creative kid to build an endless number of "products"; products that are fun to create, but also very inspiring to others, and useful, if not indispensible: aiding development and improving health in rural areas of our globe, combating climate change, increasing energy security, creating green jobs, and more.

T. Patrick Walsh of Greenlight Planet Inc., and Scott Brusaw of Solar Roadways share their passion and entrepreneurial drive with the readers of Future Photovoltaics. Read and enjoy.

Driving Into the Future: Solar Roadways

Scott Brusaw
Solar Roadways

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Abstract

A Solar Roadway is built out of Solar Road Panels: structurally engineered cases that can be driven upon and contain electronics including solar cells and LEDs. The generation of electricity allows the Solar Roadway (or parking lot, airstrip, playground, bike path, etc.) to pay for itself over its life span.

Somewhere around six years of age, I received my first slot car track. Remember the little electric cars that rode on metal rails? The more you squeezed the trigger of your hand-held controller, the faster they'd go. I was amazed and started thinking about real roads. If we could only make them electric, then kids could drive and relieve our parents of the burden.

My wife and I live in north Idaho, where the air is clean, the birds are always singing and life seemed perfect. That is, until Al Gore came along and ruined it for us by introducing phrases like "global warming" and "climate crisis." At first I didn't pay much attention to the problem. I figured somebody was bound to fix it, right?

I've always hated litterbugs as much as the next guy, but I would have never labeled myself an environmentalist. My wife had always considered herself one though. At her request, we saw Al Gore's movie, "An Inconvenient Truth," and began educating ourselves on the climate crisis debate. We eventually bought the movie and book. I don't know how many barrels of oil were required to make the DVD or how many trees had to give their lives for the hard copy of the book, but we've since bought a Kindle, which will save future trees, but caused Borders bookstore to file for Chapter 11. No one said that becoming an environmentalist would be easy.

During our studies, we learned that renewable energy seemed to be the solution to the majority of greenhouse gases (50 percent from coal-fired electricity plants and another 25 percent from our exhaust pipes) that were believed to be causing the climate crisis. One day while we were adding rabbit manure to our all-organic garden, my wife asked if I could make my electric roads out of solar panels. I suppressed a chuckle and explained that solar panels were so fragile that you couldn't even stand on them, let along drive on them.

But I started thinking: What if we could make a case that would protect the solar cells inside from the static and dynamic forces of a rogue overloaded 18-wheeler locking up its brakes at 80 mph? After all, what is the black box on an airplane other than a structurally engineered case to protect sensitive electronics through the worst of airplane disasters? So I rolled up my sleeves and got to work.

This case would have to be transparent on the top to allow the sunlight to reach the solar cells. I looked up the No. 1 and 2 materials labs in the nation. They were Penn State University's Materials Research Institute and the University of Dayton's (UD) Research Institute respectively (I received my bachelor's and master's degrees in electrical engineering from UD and had no idea that they even *had* a materials research lab!). I visited both universities and learned quite a bit. Plastic "yellows" under the sun, which affects its transmissivity (the ability of the material to pass light through to the solar cells beneath). I learned that glass falls on the hardness scale between steel and stainless steel, and you can do a whole lot more with it than just make windows that can be knocked out with a well-placed baseball. They actually have glass that can bend like a piece of paper. They also make glass that is bulletproof and even bomb resistant. It's a lot tougher than I had ever imagined. I learned that glass can be textured to provide traction, so we wouldn't have to worry about all the vehicles sliding off the road the first time it rains.

We started meeting with civil engineers, structural engineers, other electrical engineers, power transfer engineers, hydrologists, forestry experts, utility companies and other experts in every field we could imagine would affect our project. We were looking for reasons that it couldn't be done, but none of these experts doubted that a solar panel could be built to withstand the abuse of traffic or that a solar road could become the new power grid.

Armed with this knowledge, we now believed that we could make glass-covered solar panels that could be driven upon. We went back to work brainstorming new features of our Solar Roadways system. Living in north Idaho, we get a lot of snow. To keep the solar cells functioning, we'd have to prevent snow from accumulating on the road surface. That meant adding a heating element to the surface: something similar to the rear window of a car. Melting the snow wasn't enough, however: We couldn't just let the water run off the side of the road and refreeze,

Figure 1 – Author's Point of Enlightenment

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or it would cause heaving and destroy our road. A storm water redistribution system was the answer: Remove the particulates through something similar to a French drain and store the storm water in tanks below the frost line. This cool water could be used to warm the surface during the winter, or cool the surface during the summer. Or, the water can be pumped to a filtration facility, an agricultural center, an aquifer, a sewer system or just the nearest body of water.

Painting road lines over solar cells would also present a problem. We live on a long, winding mountainous road. Now that we were in our late 40s, we were having a harder time seeing those road lines at night. Many people tell us they have the same problem and pray they get to their destination in one piece. Instead of painting road lines, what if we placed yellow and white LEDs in the case to light up the road lines from beneath? Instead of straining to see where the road lines were at night, it would be like driving on a runway or in a video game. We learned that similar experiments in the U.K. reduced nighttime accidents by 70 percent.

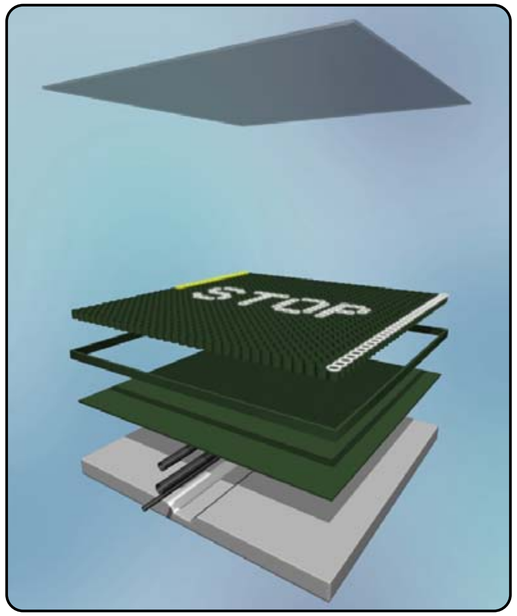

Figure 2 – Exploded View of the Initial Solar Road Panel *Courtesy of Dan Walden*

Adding LEDs meant we'd have to add a microprocessor to drive them. Adding a microprocessor makes each Solar Road Panel a communications device, which allows a central control station to reconfigure the road lines instantaneously. They can reroute traffic, spell out warnings in the road, create detours, etc. This not only solved a problem, but inadvertently increased the "coolness factor" tenfold according to resounding responses we received.

My wife requested a system for preventing vehicle/animal collisions, so back to the drawing board I went. Placing load cells in the panels would allow the road to know when something was on its surface: If a deer walked onto the road, the road would know it. The panels could warn the oncoming driver (also detected by the road) of a problem on the road ahead via an LED message in the road itself. I realized this would also allow suspected terrorists to be tracked by the road in real time via RFID tags placed on their vehicles. Hazardous materials shipments could be tracked in real time the same way. Autonomous vehicles could finally become a reality. Homeland Security was going to love this.

Our wheels were really turning now: Why limit our product to roads? There are plenty of driveways, parking lots, sidewalks, playgrounds, bike paths, race tracks, amusement parks, airports, cruise ship decks, oil tanker decks, etc. – basically anything with a hard surface that is exposed to the sun can be covered with structurally engineered solar panels.

So what does one do when one has a great idea and no business or marketing experience? Naturally, you start a website and share your plans with the world. Slowly, we started getting noticed and a few websites started writing articles about us. People began to email us to either tell us we were brilliant or insane. We weren't really surprised: Some of our children were beginning to question our sanity. Although we were familiar with blogs and bloggers, we'd never had their full attention directed at us. It was quite a learning experience: While the truly educated seemed to recognize the potential of such a system, the failed science majors were having a field day. The possibilities kept growing and features continued to be added, with the bloggers on dozens of new articles both singing our praises and telling us we couldn't possibly be serious. I often wondered what the Wright Brothers would have done if there had been an Internet around 1900 and they had announced they'd fly a heavier-than-air machine. The bloggers would have eaten them alive. Hopefully they would have done what we learned to do: develop a thick skin and a good sense of humor and press forward.

A bigger problem was looming on the horizon: Would the powers that "rule the road" allow us to just go out and start slapping our panels onto public roads and highways? We began to realize that the DOT, DOE, EPA, Homeland Security and probably half a dozen other agencies would have to not only approve it, but learn to work together to make it happen. It began to sink in that this could be the hardest part of the whole project – the actual engineering paled in comparison.

A trio who called themselves YERT (Your Environmental Road Trip – yert.com) was in the process of touring all 50 states in 52 weeks to find solutions to global warming. They had read an online article about us and asked if they could stop by while in Idaho for a quick interview. It worked out well for both of us: They got a story and I got our first video to post on our website.

In 2008, a company called Booz Allen Hamilton sent us an email requesting we do a presentation about Solar Roadways at their headquarters in Virginia. We had never heard of them and they sounded like an alcohol company, so we didn't respond. Several days later, my wife looked up the company. To our horror, we had been ignoring the oldest consulting firm in the nation, which had contracts with the DOT, DOE, EPA, Homeland Security and probably half a dozen other agencies that we would need. They had merged the NFL and the AFL! Before you could say, "Coal can't be made clean," we were on a train headed East.

It was our first big presentation, and it went well. In the crowd was a representative from the Federal Highway Administration (FHWA). After the presentation, he asked if we'd be in town long enough to do our presentation for his group. We figured if anyone was going to throw us out on our ear, it'd be these guys.

Two days later, we presented the Solar Roadways to the FHWA. Miracle of mira-

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cles, they were friendly and helpful. What they particularly liked was the thought of a road that could pay for itself through the generation of electricity. It turns out that road construction materials tend to follow the price of a barrel of oil: Asphalt is petroleum-based, after all. We didn't realize it at the time, but our project could not have come at a more perfect time in history: Our infrastructure was falling apart, the price of asphalt and other traditional materials for building roads had skyrocketed, and our country was ready to do something about our antiquated highway system and start thinking about a true smart grid.

Between the presentations, we met with several congressmen and senators at their offices across the Potomac. While they were all encouraging and friendly, none of them threw large sums of cash at us as we had hoped. "It's an election year," they said, which was apparently the wrong time to be looking for funding. We then met with one of our own Idaho congressman, who told us he could earmark us on a bill in January. He was soundly defeated in November, probably because of excessive earmarking.

In 2009, the DOT came out with an SBIR solicitation for a new paving system that could pay for itself over its life span. We learned that the Federal Highway Trust Fund was broke, as were the state DOT budgets. We applied for the contract with our Solar Roadways project and were awarded a six-month $100,000 Phase I contract to develop a crude prototype Solar Road Panel. We turned in our final report and a video demonstration of the system. YERT visited us once again and filmed a demonstration of the prototype and placed it on YouTube. This technical video is now approaching 1 million views: http://www.youtube.com/watch?v=Ep4L18zOEYI. I'm still amazed – we now have a worldwide fan base and can't begin to keep up with our email inbox. YERT has now shot over 10 hours of Solar Roadways video and plans to produce a full-length documentary about the origins of the Solar Roadways project.

Figure 3 – Artist's Rendition of a Solar Roadway *Courtesy of Dan Walden*

Since the Solar Roadways double as the nation's power grid, we'll be killing two birds with one stone (only metaphorically, fellow environmentalists). Our government is looking for an intelligent highway system, a self-healing, decentralized, clean renewable power generation system, and a smart grid. That's precisely what Solar Roadways offers.

With a decentralized power generation and distribution system, a DC grid makes a lot more sense. Currently, each Solar Road Panel (or any typical solar panel) would need its own micro-inverter to perform independently and feed into an AC grid. By generating power near the end user, AC power may no longer be needed. Most of the devices we plug into our wall outlets immediately convert the AC to DC to perform the work. If we created a DC standard for household use, then manufacturers of appliances could remove the AC-to-DC conversion circuitry, which would cut down on costs and conversion losses. We'd also eliminate the need for DC-to-AC inverters. Thomas Edison would be ecstatic.

Since Solar Roadways are, by definition, already in the right-of-way, no special land need be set aside for solar farms. The roads are already there – why not put them to use? One of the problems facing wind farms is the challenge of getting the wind power to the grid. If the nearest road serves as the grid, then all you'd need do is "pave" the road leading up to each windmill with Solar Road Panels. Can you imagine solar solving the wind problem? This holds true of every kind of renewable energy. Solar Roadways could become the backbone for all forms of renewable – past, present and future.

The FHWA has told us they want us to target parking lots first, which makes a lot of sense: Parking lots typically have slow-moving lightweight vehicles. They want us to learn our lessons and perfect our technology before moving out onto public roads. Smart folks.

The Achilles' heel of electric vehicles (EVs) is that they have a limited range: usually around 100-150 miles. That makes them great for around-town driving, but you're not currently able to take them for a long-distance family vacation, unless your destination is the side of a road 150 miles from home. Suppose we could persuade one national fast-food chain to green their image by retrofitting their parking lots nationwide with Solar Road Panels. Let's use McDonald's for our example. If all I have to do is find the golden arches to recharge my EV, then I can drive it from California to New York. I challenge anyone to find a 100-mile stretch of American highway without a set of golden arches.

With this capability, EVs could finally become practical. Drivers could start trading in their gas guzzlers for EVs. Our dependency on oil would begin to subside. Taco Bell, KFC and Burger King would see the writing on the wall: McDonald's would be getting all of the business from the increasing number of EV owners. More and more businesses would now be using solar rather than coal. Environmentalists would be dancing in the streets, along with all of the solar cell manufacturers.

<< PREVIOUS PAGE | NEXT PAGE >>

There are over 28,000 square miles of asphalt and concrete surfaces exposed to the sun in the U.S. alone. Covering these surfaces with 12’ by 12’ Solar Road Panels would require roughly 5 billion panels. Even at today’s standard of 15 percent efficient solar cells, that area could produce three times more electricity than we’ve ever used as a nation (for a breakdown of the numbers, see our numbers page: http://www.SolarRoadways.com/numbers.shtml). That’s almost enough to power the entire world. If the Solar Roadways provided power during daylight hours, and (assuming that no clever individual is ever able to create a practical energy storage system) wind, hydro and nuclear can take up the slack at night, then we could finally be done with coal.

Manufacturing 5 billion Solar Road Panels would do to unemployment what a good solar array can do to a utility meter: We could spin it backward and produce more jobs than we could fill. It’s not just the final assembly, installation and maintenance, but every component that goes into the panels: the manufacturers of solar cells, LEDs, microprocessors, glass, etc., will have to ramp up. We could manufacture our way out of this economic slump and become an exporter of energy for the first time in decades.

At the end of their anticipated 20-year life span, the Solar Road Panels would be refurbished rather than discarded. Most of the parts should be reusable. Certain elements, including the solar cells, would be updated to the latest and greatest. For instance, if we go into production tomorrow using 15 percent efficient solar cells, then 20 years from now we’d replace them with the off-the-shelf norm of the day – 60 percent? This same Solar Road Panel would then be capable of producing four times more electricity than it did previously. This allows the system to keep up with the increased demand in electricity over the years and it also provides job security for many of you reading this article!

It is said that necessity is the mother of invention. Not just a 6-year-old’s desire to drive a car, but rather the need to change the way we currently think and do things. Our world is waiting for us to make some big and drastic changes. Lobbyists and bloggers will continue to try to tell us otherwise, but we all know that solar is the only real solution to our future energy needs.

Note: The FHWA invited us back to apply for Phase II funding (two-year $750,000 contract to build the first Solar Road Panel parking lot). We submitted our application in January 2011.

In 2010, Solar Roadways won the prize for the most votes in GE’s Ecomagination Challenge. As of this writing, Solar Roadways is the most supported entrant in round 2 of the Ecomagination Challenge, which is focused on products for the homeowner. ■

ABOUT THE AUTHOR

Scott Brusaw *is president & CEO of Solar Roadways Inc. He is an electrical engineer (MSEE) with over 20 years of industry experience. Brusaw has multiple patents, and his hardware and software have been sold internationally.*

☞Click here to return to Table of Contents

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Kerosene Parity

T. Patrick Walsh
Greenlight Planet Inc.

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The quest to replace fossil-fueled electrical grids with solar energy has been the underlying motivator for most progress in photovoltaics – the focus of researchers, entrepreneurs and policymakers. Humanity’s desperate need for a renewable alternative makes grid parity both a noble and lucrative goal. But the most desperate quarter of humanity, namely the 1.6 billion rural people living without electricity in developing countries, pay far higher energy prices than do grid-connected people. For developing-world villagers, existing photovoltaic technology is already the most economical energy source for myriad needs. Understanding, let alone designing for, these needs is difficult for most of us in the photovoltaics community, if only because our prior life experiences are often a world apart from villagers’. But the effort to understand and address this market is worth it: Designing products, businesses and policies to get photovoltaics into the hands of underserved rural consumers is good, it’s profitable and it’s downright fun.

As a kid growing up in Chicago, I thought I was afraid of the dark. But in truth, the ever-present glow of a city meant that true darkness was something I had barely experienced. It wasn’t until driving up a dirt road into an Indian village in the summer of 2005, my sophomore year of college, that I experienced life beyond the reach of power lines. I had set out with a handful of friends from college as a newly formed chapter of


Woman Cooking With
Dim Dark Kerosene Lamps


Woman Cooking With
the Bright Light of the Sun King

<< PREVIOUS PAGE | NEXT PAGE >>

Engineers Without Borders, planning to spend the summer installing an experimental bio-diesel generator in Badakamandara, population 800.

That first evening in town, swarmed by children who were as fascinated by my digital camera as I was in taking their photos, the setting sun prompted me to walk inside the one-room building where I would sleep for the next two months, and reach for the light switch. But as I groped along the concrete wall, my fingers found nothing. Being in town specifically to install an electrical generator, it should have been no surprise that there was no light switch. But the sudden realization that it was getting dark, and I was completely without power for the foreseeable *months*, inspired an unexpectedly visceral shock: It was a mild but real sense of desperation that I will not forget.

As night fell, villagers lit kerosene lanterns; first a handful, and soon dozens. I had only seen these flickering, smoky relics before in movies. But it immediately became apparent how essential the kerosene lamp was, however dim and inefficient.

As a month passed and our complicated, expensive generator installation approached completion, the simplicity and ubiquity of the kerosene lamps stuck in my mind. Despite being woefully outdated technology, it remained the de facto standard for one reason: In the absence of government-organized utilities, it was the light source that villagers could purchase individually, to solve their personal, immediate need for light, without relying on any network.

A typical Indian village family spends $2 per month on kerosene, which is subsidized. (African villagers often spend twice or three times as much on the open market.) For people who earn less than $2 per day, this is a huge cost for a few hours of dim, smoky lighting: The brightness is equivalent to roughly 5 percent of a 60-watt incandescent bulb. And since light from a flame is hard to direct downward, most goes straight up, to be wasted on the hut's dark ceiling.

Starting around 2005, photovoltaic and light-emitting diode (LED) technology converged to the point where an amazing new combination became possible: With a tiny, half-watt solar module, a small battery and an efficient LED, one can now assemble a solar LED lantern that charges during the day, and at night yields more usable light than the kerosene lamp, all at an off-the-shelf cost of around $15. By purchasing such a solar lantern, most villagers could earn back their investment through reduced kerosene costs within half a year, and reduce their overall lighting expenditure by 80 percent over a three-year product lifetime.

Brothers Study in Kenya

From my view in Badakamandara, it seemed like a foregone conclusion that this convergence would kill the kerosene lamp within a decade. I decided to set aside the centralized plans and philanthropy of our NGO and start a sustainable, for-profit business to commercialize the technology. So far, Greenlight Planet Inc. has lit up half a million lives with our clean, safe, affordable Sun King™ solar lanterns, designed with village needs in mind. The lamps eliminate a major source of indoor air pollution. They significantly reduce global greenhouse gas emissions from lighting. They save villagers money. They allow men and women to pursue cottage-industry work at night, and children to study, all without worrying about the cost and fire hazard of kerosene. And perhaps most importantly to villagers, the new lamps are cool: They are a means to, and also a symbol of, a higher standard of living.

As photovoltaics becomes more efficient and the power requirements of other electronic technologies fall, new opportunities come into play every year. In 2005, to find a pay phone, I had to drive half an hour from Badakamandara. By last year, in a startling shift seen around the developing world, I watched villagers tend to cattle, eyes all the while glued to text messages on inexpensive

Family Living With Sun King

<< PREVIOUS PAGE | NEXT PAGE >>

mobile phones. But with mobile-phone penetration soaring, power lines are still a distant dream, leaving villagers to pay 15 to 25 cents at a local shop every time they need to charge their phone: This charging often costs more than the phone service. So after countless requests, Greenlight Planet's newest product includes adapters for charging a wide variety of these low-cost phones.

Designing appropriate new photovoltaic applications for these rural markets is now a principal challenge. But in terms of photovoltaics themselves, much important innovation remains to optimize the underlying technology for the village. At the semiconductor level, thin films will take over this market in the future if they can achieve even modest efficiency gains: For small modules, the benefit of doing away with manual soldering of individual crystalline cells is enormous, but above about 1 watt, the low efficiency of thin films means the modules are too bulky to efficiently package and ship with a low-cost consumer product. At the module level, due to the small size of the modules, the cost and design of encapsulation technology is critically important: Solar cells themselves account for a large fraction of the cost of a large solar module, but the semiconductor accounts for less than half the cost of the finished module in the case of a 1-watt panel, using traditional assembly and encapsulation processes. In the realm of solar concentrators, a very small-scale concentrator could be a major boon for the village but would require redesigning with an entirely different cost/benefit analysis in mind relative to traditional large-scale concentrators, considering, for example, how to minimize setup and maintenance complications for millions of end consumers.

For photovoltaics researchers who may be impatient for grid parity, the knowledge that millions of kids are now studying by the light of solar lanterns (while saving their lungs, and their family's precious income to spend on something other than fossil fuel) should be an enormous source of pride: Decades of research have already pushed photovoltaics well past kerosene parity, which was the key metric for the people in most desperate need of an energy alternative. Although this massive consumer market is not as obvious or as accessible to Western technologists, investors and policymakers as markets closer to our experience, the corporate strategist C.K. Prahalad had it right when he predicted a fortune waiting at the "bottom of the pyramid." And getting there is as fun as it is profitable. ■

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T. Patrick Walsh *is founder and chief technology officer of Greenlight Planet Inc. He founded the company while in college at the University of Illinois, where he studied engineering physics and economics, graduating in 2007. The company distributes a direct replacement for kerosene lamps: affordable solar-powered LED lanterns that villagers buy to light up their own homes, with no philanthropy or public infrastructure required. Patrick has become a recognized mass-affordability product designer, garnering notable awards from Lemelson-MIT, UNESCO and the Lighting Africa program.*

☞Click here to return to Table of Contents

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NEW TECHNOLOGIES & MATERIALS

Click here to return to Table of Contents PRINT this article E-MAIL this article

Jef Poortmans
Department Director, Solar and Organic Technologies, imec

Reducing PV production costs with thinner cells

The PV industry is rapidly maturing. We are on a fairly long and stable path to lower the costs of energy generated with solar modules. It is a path that is dictated by the economic realities. On the one hand, we have to produce solar cells cost-effectively. That inevitably leads to larger-scale production and industry consolidation. On the other hand, there is still some way to go before PV technologies reach grid parity. So we have to keep improving the technology, and look for advanced and novel concepts that can permanently close the gap with grid parity.

In the article in this section, K.V. Ravi from Crystal Solar, Inc. discusses two related topics. The more general topic is scaling in PV technologies, which is quite different from how scaling is understood in the semiconductor industry. Dr. Ravi especially goes into the efforts of the industry to reduce the thickness of absorber layers, lowering the production costs by using less material, the material cost being an important part of the total costs. This can be done by moving to materials with higher absorption coefficient (a-Si:H, CIGS, CdTe, etc.). But also for crystalline Si solar cells, thinner active layers can yield higher efficiencies, through the use of proper optical designs. Dr. Ravi makes the point that the current cell thickness is largely imposed by the difficulty of handling much thinner wafers. He then discusses the technology that is being developed at Crystal Solar – fabricating 50 µm thin wafers through epitaxial deposition. Of course, the handling issues still apply, so Crystal Solar is also working on new approaches for handling, processing and packaging.

Thin Is In, But Not Too Thin!

K.V. Ravi
Crystal Solar, Inc.

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Abstract

The trade-off between thick (~170 microns) silicon-based PV and thin (a few microns) film non-silicon and amorphous silicon PV is addressed by the development of single crystal silicon wafers of thicknesses of ~50 microns produced by epitaxy. This approach has the cost advantages of thin film technologies and the efficiency, reliability and non-toxicity of earth-abundant silicon PV.

Semiconductor technologies, of which photovoltaics is an increasingly large part, have had an obsession with dimensions and scaling over their history for increasing product functionality and reducing manufacturing costs. The most familiar and the most impactful is the ubiquitous scaling of gate dimensions in integrated circuits as described and predicted by Moore's Law. This remarkable scaling of the critical dimensions in transistors in integrated circuits has been the driving force for the information, communication and entertainment industries. An additional important scaling in semiconductor manufacture has been silicon wafer size changes to improve the economics of manufacturing. Typically there have been wafer size (diameter) increases roughly every 10 years for about the last ~20 to 30 years, with the current leading-edge factories being based on 300 mm diameter wafers.

Scaling in photovoltaics has taken a different path. Clearly the analogy with semiconductor critical dimension scaling does not apply to photovoltaics where the device dimensions are equal to the wafer dimensions. In crystalline silicon photovoltaics, wafer size scaling is also not a very important factor, since very large wafers would lead to extremely unwieldy devices with large currents and low voltages limited by the band gap of silicon. Consequently, manufacturing cost reductions in photovoltaics are not dominated by wafer size changes.

The primary scaling factor in photovoltaics has been the thickness of the semiconductor or the absorber driven by manufacturing cost reasons, since materials constitute the major portion of manufacturing costs. There are, generally, two approaches to thickness scaling. The more fundamental one is based on the absorption coefficient of the semiconductor. Silicon, an indirect band gap semiconductor, has a low absorption coefficient for light, necessitating the use of fairly thick wafers (~180 microns today) to absorb a large portion of the sun's spectrum that silicon is sensitive to and, more importantly, the difficulty of handling and processing silicon wafers of thicknesses much below current ~180 micron thickness. A response to the need to use thick silicon wafers has been the development of photovoltaic devices using direct band gap semiconductors such as amorphous silicon and various compound semiconductors with cadmium telluride (CdTe) and copper indium gallium selenide (CIGS) being the current favorites. These materials have superior absorption coefficients, enabling the use of very thin films of these materials and manufacturing technologies based on depositing thin films on rigid substrates such as glass or metal sheets.

With the current state of photovoltaic technology, there is a trade-off between reduced materials usage with thin film compound semiconductor (and amorphous silicon) photovoltaics and the relatively low energy conversion efficiency of these products. In contrast silicon wafer based devices, although consuming too much material are the undisputed leaders in achieved high energy conversion efficiencies.

Recently there has been a great deal of interest in CdTe and CIGS based photovoltaics with CdTe being the current leader in volume manufacture. However several issues confront these materials if truly large scale deployment is contemplated. This includes toxicity of these materials although many companies claim to have

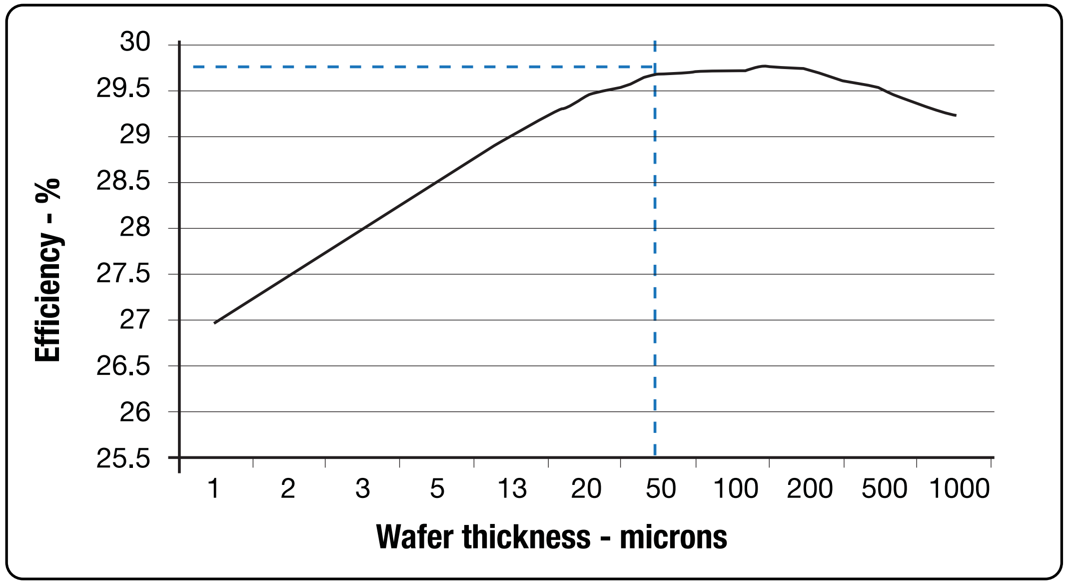

Figure 1 – Efficiency as a Function of Wafer Thickness

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this under control. Another much more difficult issue with these materials is their availability. As Martin Green states, "In success CdTe and CIGS technologies will ultimately guarantee their eventual failure. This will be by pushing Te and In prices beyond the threshold for profitability, as recently with polysilicon prices."[1]

In view of the above, although "thin is in" a case can be made for not being too thin! This case is based on the fact that silicon wafer thicknesses in today's high-volume manufacturing technology are much thicker than needed for achieving high energy conversion with the thickness being driven by the difficulty of handling and processing wafers of thicknesses much below about 160 µm. Figure 1[2] shows that the minimum wafer thickness required to achieve the theoretical maximum efficiency from silicon solar cells is ~40 to 50 microns, not the current ~180 microns.

However, in addition to the basic problem of slicing silicon ingots into wafers of these thicknesses and the inevitability of kerf loss, handling and processing such thin silicon wafers are basically impossible tasks. The technology limitation of current wafer-based technology from the perspective of wafer thickness can be seen in Figure 2.

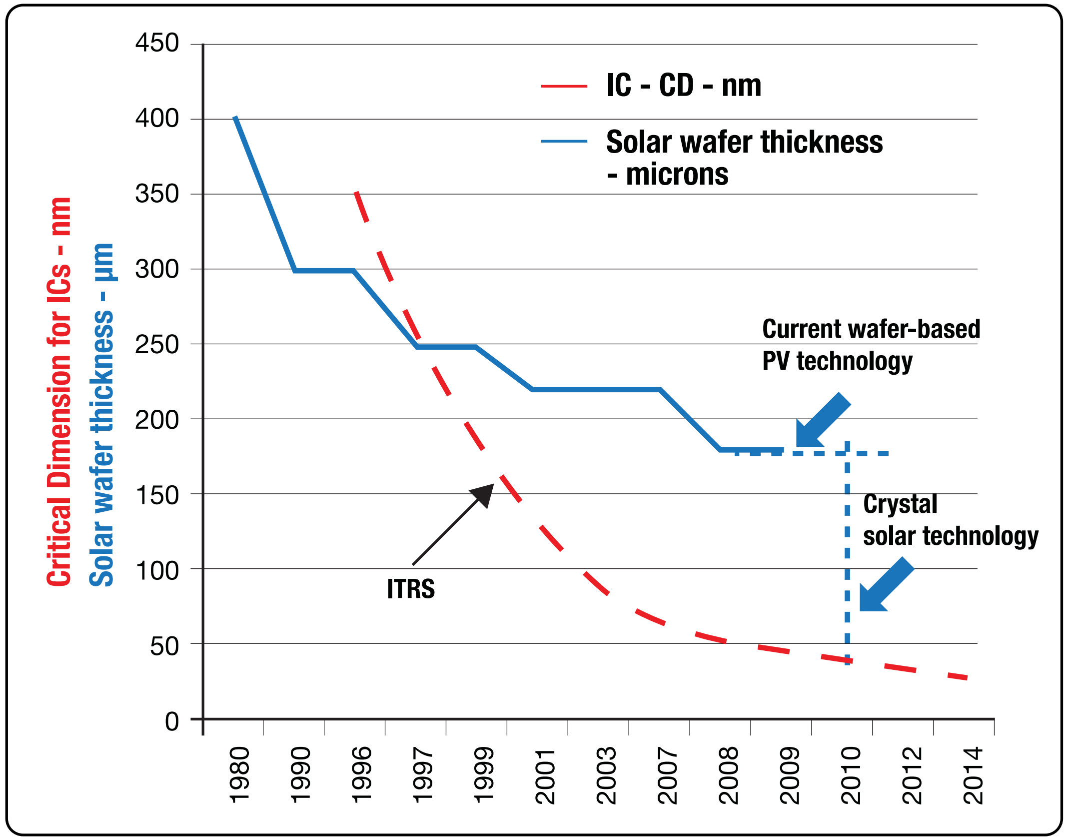

Figure 2 – Moore's Law for PV?

In loose analogy with the continuing reduction in the critical dimensions for integrated circuits, the continuing reduction in wafer thickness has been called the Moore's Law for PV (Figure 2). In further analogy with Moore's Law for ICs, where continuing reduction in the CD is slowing down due to fundamental limitations, wafer thickness reductions for PV are also slowing down, due to fundamental limitations. Both technologies need radical departures from conventional scaling.

Crystal Solar is developing such a radical departure from conventional practice for manufacturing solar cells with an absorber (wafer) thickness that is, as Goldilocks would say it, it is neither too thick nor too thin, but just right! This technology is based on fabricating single crystal wafers by depositing silicon from the vapor phase on to appropriately prepared substrates using an epitaxial deposition process. The positioning of this technology is depicted in Figure 3.

This approach enables the fabrication, handling, processing and packaging of very thin (< 50 microns thick) single crystal silicon wafers and solar cells. This will substantially reduce the amount of silicon utilized with a major impact on the overall materials usage in PV manufacturing. When this technology is transitioned into manufacturing, we project direct manufacturing costs well under \$1/Wp to be achievable with high-effi-

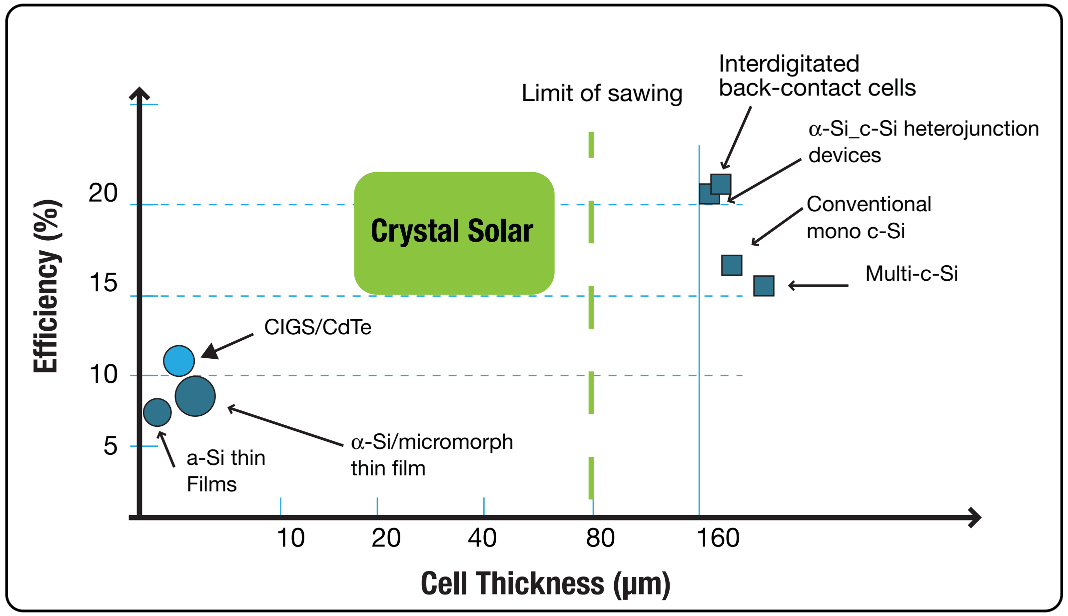

Figure 3 – Cell Efficiency for Various Thickness Semiconductors

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ciency PV modules with a direct impact on lowering systems costs. This technology will have the disruptive potential to dramatically reduce manufacturing costs as follows:

- Silicon utilization is reduced to about 20 percent of that utilized in current wafer-based technology – ~300 µm (slice + kerf) for current technology versus < 50 µm using epitaxial technology.
- The traditional supply chain – polysilicon production in Siemens reactors, crystal growth or casting, ingot cropping, squaring and wafering – are eliminated by the direct gas (trichlorosilane)-to-wafer process involving epitaxy (Figure 4). This reduces process complexity and is substantially more capital-efficient as compared to traditional technology.

Although high-quality, very thin silicon wafers can be produced by this approach, novel and innovative approaches have to be developed for handling, processing and packaging.

Figure 5 – ~1 ft. X 1 ft. Mini Modules With Square, ~50 Micron Thick Solar Cells Produced by Epitaxy

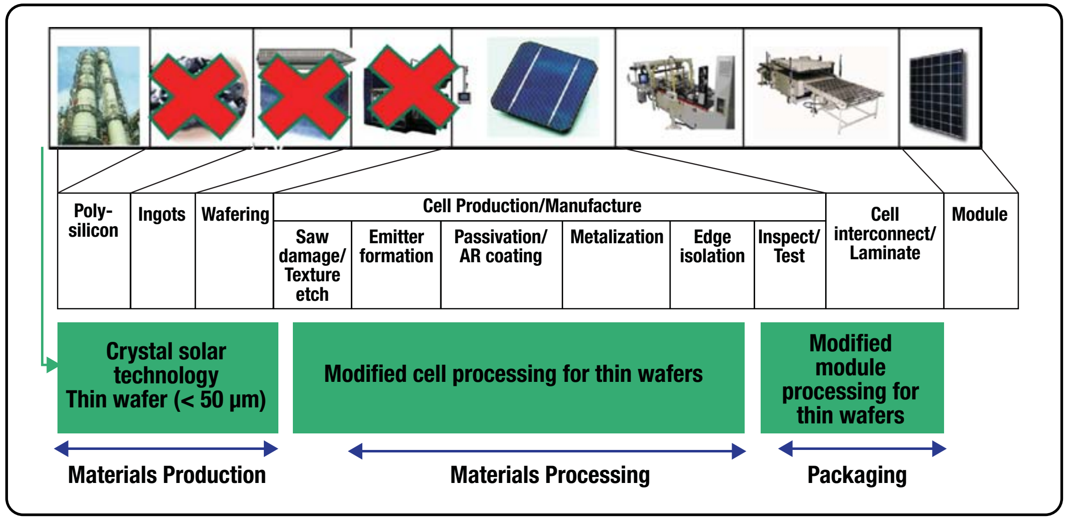

Figure 4 – The front end of the current PV supply chain involving the production of polysilicon from trichlorosilane (TCS), the growth of ingots and the machining and wafering of ingots are eliminated with the Crystal Solar direct gas-(TCS)-to-wafer process.

At Crystal Solar, such processes have been developed for fabricating very thin solar cells and packaging them for the completed PV module. Figure 5 shows an example of mini modules ~1 ft. X 1 ft. using ~50 micron thick solar cells.

When transitioned into volume manufacturing, this technology is expected to enable the lowest manufacturing costs of all PV technologies with the cost advantages of thin film technologies and the efficiency, reliability and non-toxicity of earth-abundant silicon PV.

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K.V. Ravi *is the chief technology officer of Crystal Solar, where he is responsible for the development of technology for the manufacturing of low-cost silicon wafers, solar cells and modules. His other affiliations have been Applied Materials, Intel, Motorola, Texas Instruments and Mobil Solar Energy Corporation. He has a Ph.D. in materials science from Case Western University.*

☞Click here to return to Table of Contents

PRINT this article
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<< PREVIOUS PAGE | NEXT PAGE >>

Click here to return to Table of Contents PRINT this article E-MAIL this article

Jörg W. Müller
Director, R&D Cells; Q-Cells SE

Photovoltaics is one of the fastest-growing electricity generation technologies in the world. Average annual growth rates of global PV installations have been around 45 percent for the last 15 years, which, in combination with typical learning rates of 20 percent, lead to fast and ongoing cost reductions in the industry.

Today the photovoltaics marketplace is experiencing rapid decline in average selling prices of solar cells and modules. This price decline is a mandatory prerequisite to making PV competitive with fossil and nuclear power in terms of retail or even wholesale electricity prices. Manufacturers are thus being challenged to dramatically reduce operational costs while at the same time increase cell efficiency and quality in order to remain competitive.

One way to increase cell efficiencies is the use of n-type silicon, which is known to yield higher-quality wafers compared to p-doped wafers commonly used in the PV industry. SunPower and Sanyo, for example, manufacture solar cells with efficiencies exceeding 20 percent using n-type silicon. Both companies are employing a cell process different from the industrial standard, e.g., interdigitated back contact cells and heterojunction with intrinsic thin layer, respectively.

A more favorable path toward high cell efficiencies would be a simple and low-cost industrial process for n-type silicon similar to today's p-type screen-printed standard process without sacrificing the efficiency potential of n-type wafers.

Researchers from the International Solar Energy Research Center in Konstanz are working in close cooperation with Bosch Solar Energy on such a simple industrial process for n-type solar cells. They demonstrate very high efficiencies exceeding 19 percent on large-area wafers using a boron front emitter, a phosphorus back-surface field and conventional screen printing. Apart from the achieved cell efficiencies and the simple process sequence, the exciting feature of this cell structure is its outstanding bifacial capability. The measured quantum efficiencies under front and rear illumination are almost equal. This allows fabrication of bifacial modules with significantly increased energy yield compared to standard modules of equal conversion efficiency. Depending on the mounting conditions of bifacial modules, the additional energy yield generated by illumination from the rear side could be almost as high as the contribution of the front side. These new n-type bifacial solar cells have the potential to reduce the levelized cost of electricity drastically, paving the road to PV grid parity and fuel parity, consequently making PV a major energy resource on a global scale.

N-type Bifacial Solar Cells for Industrial Application

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Increasing the conversion efficiency of solar cells is a measure to reduce the cost of energy generation of a photovoltaic system. Currently, worldwide production of solar cells is more than 80 percent based on crystalline silicon, from which more than 90 percent are produced on *p*-type doped wafers. However, the highest conversion efficiencies of commercially available crystalline silicon solar cells and modules are achieved by the company sunpower on *n*-type doped wafers. Sunpower uses an advanced cell concept called interdigitated back contact, achieving cell efficiencies of up to 24.2 percent.

But additionally for screen-printed solar cells, the *n*-type approach holds significant benefits over advanced *p*-type approaches and might therefore become a cost-effective alternative to the predominant *p*-type solar cell process with alloyed aluminium back surface field (BSF). Typical advantages of *n*-type material have already been comprehensively reviewed, such as the higher tolerance to common metal impurities[1] and the lack of a boron-oxygen-complex-related degradation. However, the mass production of *n*-type solar cells using the low-cost technique of screen printing is only now starting,[2] because processing of *n*-type wafers comprised mainly three unresolved issues: cost-effective emitter formation, passivation of p^+ emitters and contacting of p^+ emitters.

The potential for higher cell efficiencies on *n*-type base material led many groups, including ours, to develop a cost-effective process to fabricate *n*-type cells for a subsequent industrial implementation. We review here our progress and achievements of an *n*-type cell concept developed by ISC Konstanz e.V. and Bosch Solar Energy AG. Our cell process features a homogenously diffused boron emitter, which is topped by a stack of a passivating layer and microwave plasma-enhanced chemical vapor deposition (PECVD) of hydrogenated silicon nitride (SiN_x) anti-reflection coating layer. The rear side of the cell comprises a phosphorous-diffused BSF subsequently passivated by a SiN_x layer. The cell is contacted by standard screen printing using an h-grid pattern on both the front and the back side. A schematic cross section of the cell is shown in Figure 1. In contrast to a cell with an Al-alloyed BSF, this cell structure

<< PREVIOUS PAGE | NEXT PAGE >>

allows a bifacial usage with a high bifaciality factor. In appropriate applications, the bifacial character of this cell concept yields higher energy generation as compared to a monofacial cell concept of equal front-side conversion efficiency.

Boron Diffusion and Bulk Lifetime Stability

Boron is the commonly used dopant to form the emitter in *n*-type *p*-*n* junction solar cells, especially in high-efficiency cell concepts. Many diffusion sources for diffusion of boron into silicon exist. There are gas phase diffusion sources, i.e., boron tribromide (BBr_3), boron trichloride (BCl_3) and boron diborane (B_2H_6), but also boron-doped oxide as a solid or liquid phase diffusion source. The most frequently used method to bring boron into silicon is diffusion from a BBr_3 source in an open-tube furnace. In the first stage of the diffusion process (deposition), the BBr_3 is introduced into the tube at elevated temperature and mixed with oxygen, which causes it to oxidize and form boron oxide and bromine following the reaction:

$$4BBr_3 + 3O_2 \rightarrow 2B_2O_3 + 6Br_2. \quad (1)$$

Since the vapor pressure of B_2O_3 is rather low at typical diffusion temperatures (only 10^{-8} atmospheres at 920°C), liquid B_2O_3 condenses on the silicon wafer surface and on the furnace walls. The chemical reaction occurring at the silicon surface reduces the B_2O_3 to elemental boron as follows:

$$2B_2O_3 + 3Si \rightarrow 4B + 3SiO_2, \quad (2)$$

Where SiO_2 partially dissolves in liquid B_2O_3 to form the mixed phase B_2O_3-SiO_2 system (borosilicate glass, BSG). The elemental boron diffuses into silicon mostly during the second stage of the diffusion process (drive-in). At this stage of the diffusion process, a very high concentration of boron can build up at the glass-silicon interface, resulting in a boron-rich layer (BRL) formation, identified as silicon boride[3]:

$$Si + 6B \rightarrow SiB_6. \quad (3)$$

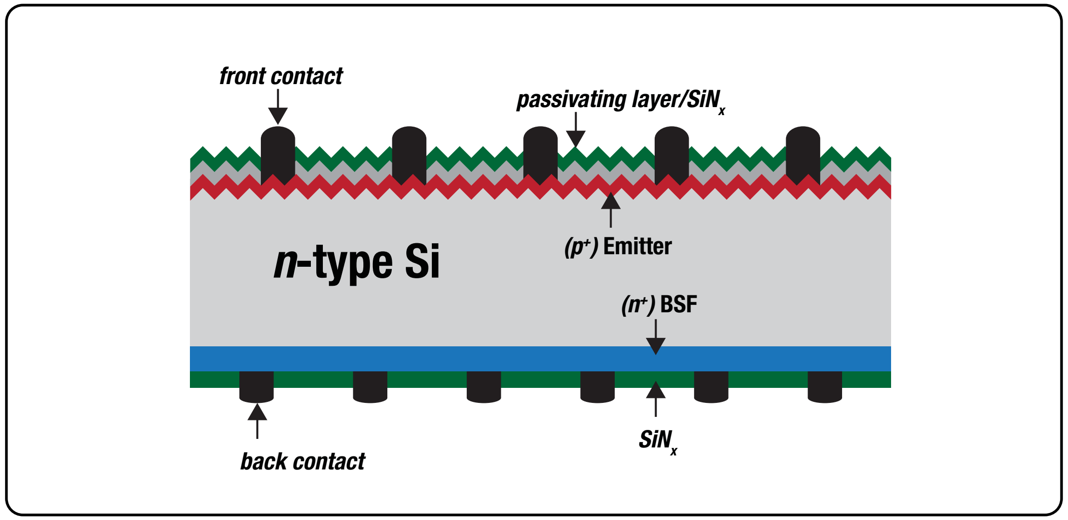

Figure 1 – Schematic Cross Section Of Our N-Type Solar Cells

The BRL is insoluble in hydrofluoric acid and it has been suspected to be responsible for bulk lifetime degradation if its thickness grows more than 5-10 nm.[4] It is known that the growth of the BRL can be suppressed if the oxygen concentration in the atmosphere increases, according to the reaction:

$$SiB_6 + \frac{11}{2}O_2 \rightarrow SiO_2 + 3B_2O_3. \quad (4)$$

For an industrial process, however, where wafers are closely packed in a relatively long boat, homogeneous diffusion over the entire batch in a relatively short process time is desirable. This implies, at the first stage of the diffusion, a very good control of BBr_3 oxidation in the tube (reaction 1) in order to slowly deposit B_2O_3 uniformly on all wafers. The formation of liquid B_2O_3 during BBr_3 step and the buildup of the BRL at the surface are the key parameters to control in boron diffusion. Therefore, homogeneous boron diffusion (from a gas source) at PV industrial requirements is more difficult to realize than the more commonly used phosphorous diffusion in the fabrication of *p*-type solar cells.

In our lab, we put considerable effort into optimizing the boron diffusion for *n*-type solar cells in a quartz tube furnace of an industrial scale. We optimized boron diffusion not only to obtain good sheet resistance, homogeneity and high throughput, but to maintain high bulk lifetime after the diffusion process. To test the bulk stability, we diffused boron at various temperatures on *n*-type Cz wafers and subsequently etched back the diffused layers. A passivation layer consisting of silicon nitride (SiN_x) was then applied on both surfaces, followed by a firing step to activate the surface passivation. The bulk lifetime was then measured by mapping the surface using the microwave-photoconductance decay (µW-PCD) method. Figure 2 shows the bulk lifetime and the sheet resistance of boron emitters using our optimized recipe. The initial lifetime measurement was performed on etched and passivated neighboring wafers before the boron diffusion process, and serves as a reference. No degradation in bulk lifetime is observed using our optimized boron diffusion that covers a sheet resistance range of 45 to 260 Ω/□. This is an indication that boron diffusion, if the chemical reactions (1-4) that govern the diffusion process are properly controlled, is not a detrimental step in the solar cell process.

Solar Cells Results and Outlook

The emitter formation and its passivation are the most crucial steps in fabricating high-efficiency solar cells. We applied our knowledge and development on boron diffusion to fabricate *n*-type cells having the same structure that is schematically depicted in Figure 1. The front surface has a random pyramid texture formed in KOH/IPA solution, while the rear side is chemically polished to

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enhance the internal rear reflection. The n^+ BSF is formed on the rear side by diffusing phosphorous from a phosphorus oxychloride (POCl$_3$) source in a quartz tube furnace. The BSF is passivated then by a standard SiN$_x$ layer. On the front boron emitter, we have applied our own developed passivation method consisting of a thin *passivating layer* and a SiN$_x$ stack. The metalization was applied on both sides of the cells by screen printing metal pastes. The cells went through a firing step to complete the contact formation.

It is important to note that in our fabrication process of *n*-type solar cells, the formation of the n^+ BSF layer, its passivation and metalization, chemical cleaning, etching or texturization steps are all standard processes used in the industry for the fabrication of *p*-type Al-BSF solar cells. No customized equipment is required to apply these steps in the industrial fabrication of *n*-type cells. The only exception is for the boron diffusion, which requires a dedicated diffusion furnace system. Therefore, our work emphasizes the understanding and development of boron diffusion for industrial applicability.

Typical cell results we obtain with our *n*-type process are summarized in Table 1. We show average values over more than 100 cells, along with the results for the best cell. The efficiency averaged at 19.1 percent, and the best cell was found to have 19.4 percent. This result underlines that the demonstrated cell concept has the potential to surpass the standard *p*-type-based concepts.

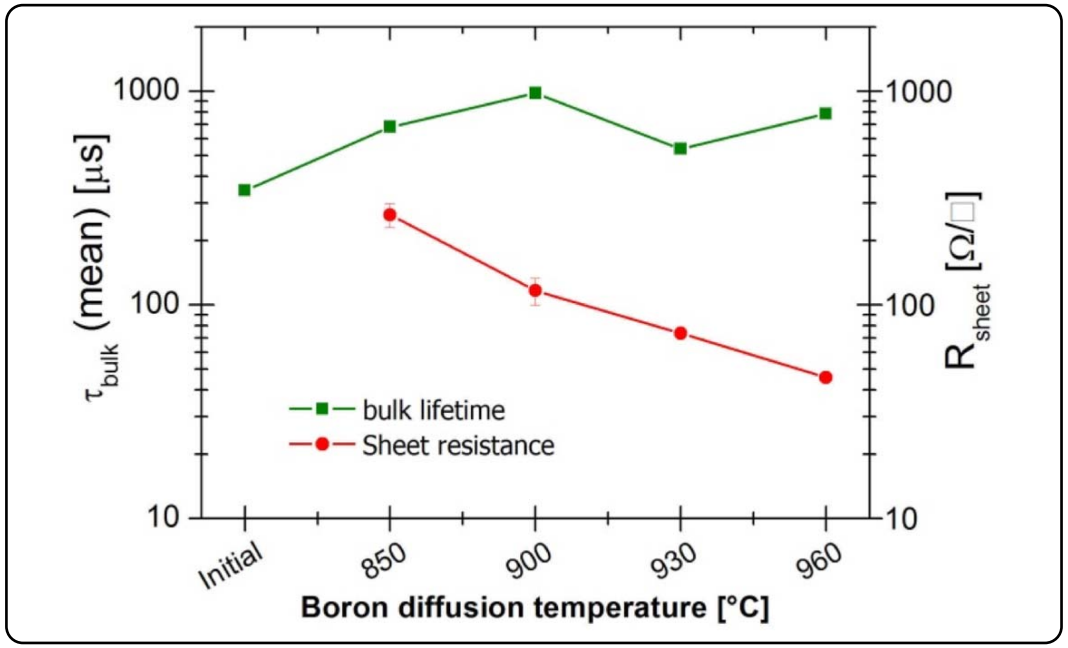

Figure 2 – Mean bulk lifetime measured on 156 mm wafers using µW-PCD on 156 mm n-type Cz wafers before and after boron diffusion at various temperatures. The corresponding sheet esistance and standard deviation of the diffused layer are also shown.

Moreover, this cell concept is bifacial, as it has an open-back side grid and passivation layer, allowing it, in appropriate applications, to generate more power than a conventional monofacial cell under the same conditions. Therefore, the performance of these *n*-type solar cells, when illuminated from the rear side, is very important.

All our solar cells processed so far have a flat back side, since they were optimized to have maximum efficiency only from the front side. This results in different short-circuit current densities (J_{sc}) under front- and back-side illumination. However, this effect can be eliminated by comparing the internal quantum efficiencies (IQE) measured under front- and back-side illumination conditions. Figure 3 shows the IQE measurement of our best cell (black circles) illuminated from the front side. The response observed at short wavelengths (below 0.5 µm) confirms the excellent passivation of the boron emitter (60 Ω/□). Moreover, Figure 3 also shows the IQE data of an optimized bifacial cell, which has different BSF sheet resistance and metalization grid (but still a flat back side) as compared with a cell optimized only for the front side. The IQE results of the bifacial cell show that, independent from which side the cell is illuminated, the response of the cell is the same. This demonstrates on one hand the outstanding passivation of the diffused surfaces and on the other hand the very high lifetime of the material, which obviously does not suffer substantially during the process.

A symmetrical IQE from both sides is an excellent characteristic because it theoretically allows fabricating bifacial cells with the same power conversion efficiencies for front- and back-side illumination, providing that the back surface is also textured. The major difference between front- and back-side performance of the cells is in the J_{sc}. Therefore, work is under way to adapt the cell process to allow for both sides to be textured in order to match the J_{sc}.

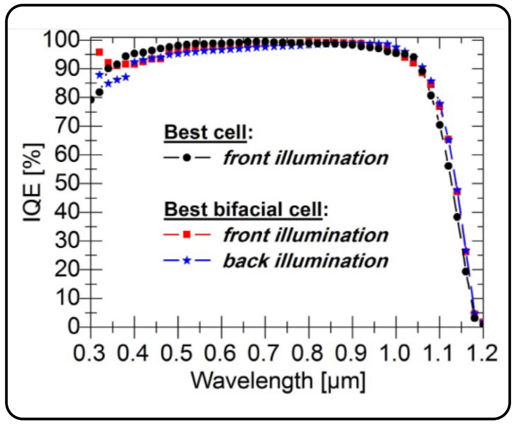

Figure 3 – Internal Quantum Efficiency (IQE) of our Best Fabricated Cell, and of a Bifacial Cell Illuminated From the Front and Back Side

	Area [cm^2]	J_{sc} [mA/cm^2]	V_{oc} [mV]	*FF* [%]	η [%]
Best cell	241	38.8	643	77.6	19.4
Average, 100 cells	241	38.3	642	77.5	19.1

Table 1 – Best Solar Cell and the Average of 100 Cells

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It could be demonstrated that the combination of proven mass production technologies and the electrical superiority of *n*-type material holds great potential for cost-effective manufacturing of high-efficiency cells in high volume. With the challenge of emitter formation, its passivation and metalization presently being solved, there is no reason for *n*-type silicon solar cells to remain a niche product.

Conclusions

We have presented a simple industrial process to fabricate *n*-type solar cells with boron front emitter and phosphorous BSF that leads to highest efficiency of 19.4 percent on large-area (241 cm^2) monocrystalline Cz-Si substrates and an average efficiency of 19.1 percent. We demonstrated that this cell concept has an outstanding bifacial capability. This feature allows for the fabrication of bifacial modules with higher energy yield as compared to the standard module of equal conversion efficiency.

Acknowledgments

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THIN FILM PHOTOVOLTAICS

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Danielle Merfeld
Director, Solar Technology Platform; GE's Global Research Center

Thin film PV continues to capture the attention of the industry with the promise of a departure from the "s-curve" described by the current c-Si PV technology era of solar. Today the range of thin film PV materials is wide and the approaches varied; however, the mantra for success is the same: Use technology to drive high efficiency at low cost. Some approaches are of particular interest based on the opportunity to deliver a high-efficiency product, as evidenced by recent lab-scale records. Others benefit from manufacturing scale and a community of researchers creating advancements on a well-known material system.

In this issue, we will hear about two different thin film approaches (CIGS and a-Si) and novel ideas about what could enable them to compete effectively in the race toward our solar future. A team from HelioVolt Corporation describes an interesting approach to depositing CIGS, which reduces the thermal budget – and associated costs – typically required with this material system. Torsten Brammer, a photovoltaics research consultant, offers an enlightening commentary on the many reasons why a-Si is an attractive choice as the technology path. He argues that a-Si delivers not just the cost and performance metrics, but also a path to sustainability; claims supported by the plethora of well-respected companies pursuing this path today.

Monolithic CIGS Photovoltaic Modules Manufactured by Reactive Transfer

Louay Eldada, Dingyuan Lu, Scott Hinson, Billy J. Stanbery
HelioVolt Corporation

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Abstract

In recent years, thin film photovoltaic (PV) companies started realizing their low manufacturing cost potential, and have been grabbing an increasingly larger market share. Copper indium gallium selenide (CIGS) is the most promising thin film PV material, having demonstrated the highest energy conversion efficiency in both cells and modules. However, most CIGS manufacturers still face the challenge of delivering a reliable and rapid manufacturing process that can scale effectively and deliver on the promise of this material system. HelioVolt has developed a reactive transfer process for CIGS absorber formation that has the benefits of good compositional control and a fast, high-quality CIGS reaction. The reactive transfer process is a two-stage CIGS fabrication method. Precursor films are deposited onto substrates and reusable cover plates in the first stage, while in the second stage, the CIGS layer is formed by rapid heating with Se confinement. High-quality CIGS films with large grains were fabricated on the production line, and high-performance monolithic modules with a form factor of 120 cm x 60 cm were produced. With conversion efficiency levels around 14 percent for cells and 12 percent for modules, HelioVolt started commercializing the process on its first production line.

Introduction

The interest in harnessing the sun for energy through PV technologies has increased tremendously in recent years, as the importance of using renewable energy has moved to the forefront of social consciousness. With their cost advantage, thin film PV technologies have been attracting significant attention. Copper indium gallium selenide (CIGS) is the most promising thin film material, having exhibited the highest thin film energy conversion efficiency. Record efficiencies of 20.3 percent for cells[1] and 15.1 percent for modules[2] have been achieved. However, it has been challenging for CIGS manufacturers to deliver a reliable and rapid manufacturing process that can be scaled effectively. In this paper, we describe such a process developed by HelioVolt and scaled up on its first 20 MW nameplate capacity production line in Austin, Texas. The process is based on reactive transfer and has the benefits of high speed, high uniformity and precise compositional control.[3]

CIGS Manufacturing Technology

Figure 1 shows the HelioVolt CIGS module manufacturing flow. The reactive transfer process can form CIGS on a variety of materials, including glass, metals and plastics. In the first product release, soda lime

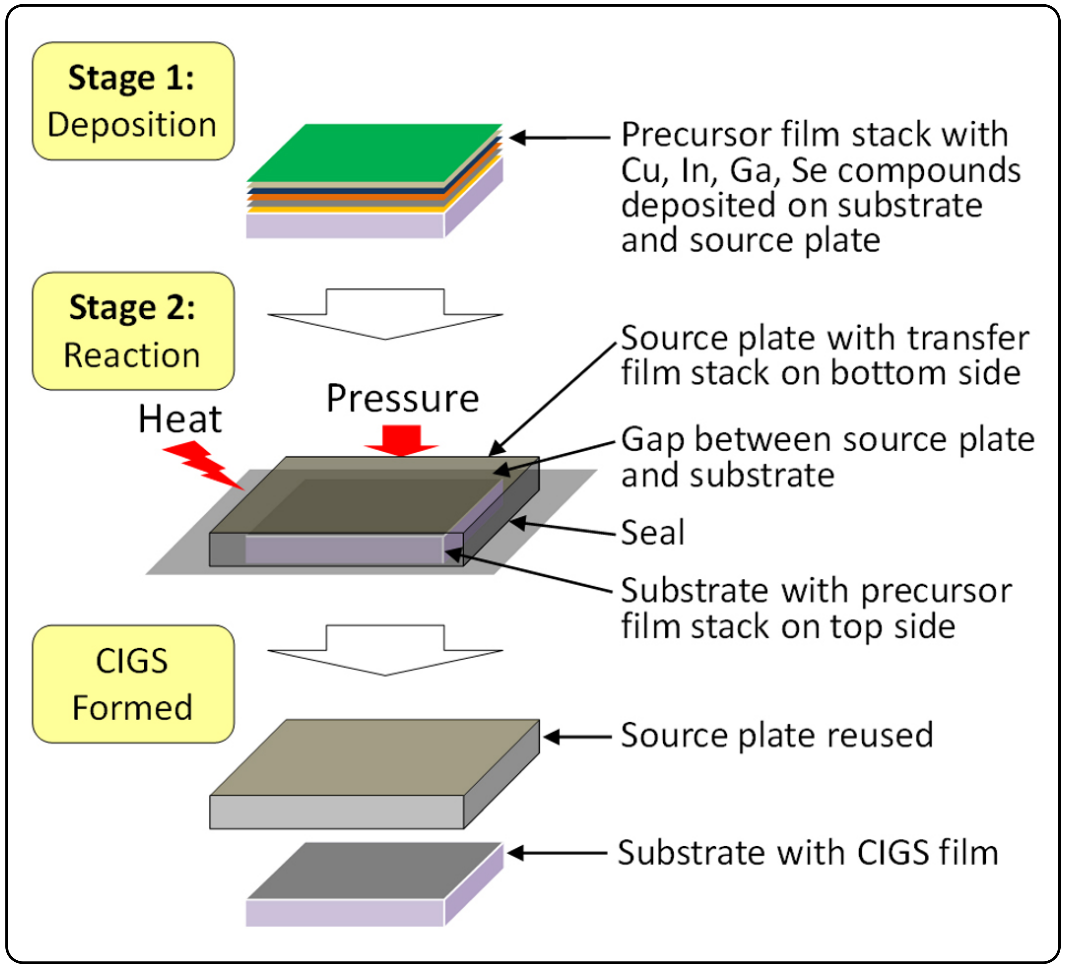

Figure 1 – Schematic of the Reactive Transfer Process

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glass (SLG) with a form factor of 120 cm x 60 cm is used as the substrate material. As SLG has a low strain point around 518°C[4], good thermal uniformity is required in processing. The monolithic interconnection scheme involves three main pattern steps, including laser and mechanical scribing. After the initial deposition step of sputtering the molybdenum (Mo) back contact film and patterning it, a two-stage field-assisted simultaneous synthesis and transfer (FASST®) reactive transfer process (Figure 1) is utilized for the formation of a high-performance thin film CIGS absorber layer.[5] In the first stage, Cu-In-Ga-Se-based precursor films are deposited onto a substrate and a cover plate, forming the chemical basis of CIGS. This film stack allows precise control of the composition and the crystalline structure, and affords different choices of processing conditions. In addition to physical vapor deposition (PVD), other rapid deposition methods, such as liquid precursor spray printing, can also be utilized.[6] Furthermore, precursors can be deposited at a low substrate temperature, enabling lower cost and higher throughput. In the second stage, these precursors are rapidly reacted under pressure, with the plates being in proximity (not in contact) and the precursor film stacks facing each other. A controlled amount of material transfers in the vapor phase from the cover plate (a reusable "source" plate) to the substrate, thereby conditioning both the bulk and the surface of the resulting CIGS film. By pulse-heating the films or by rapid thermal processing, the overall thermal budget is significantly reduced. The lower heat requirements enable the potential use of low-cost, less thermally stable substrate materials, such as polyimide. Sufficient pressure can substantially prevent the loss of selenium (Se) from the reaction zone, thereby achieving highly efficient incorporation of Se into the composition layer. The cover plates are reused after the CIGS reaction, driving the manufacturing cost even lower.

After the reactive transfer p-type CIGS formation, an optimized n-type thin buffer layer is deposited with a wet chemical process. After mechanically scribing the active materials, a layer of transparent conducting oxide (TCO) material is sputtered onto the structure, followed by the final isolation scribe. Module packaging is finished by edge sealant application, lamination and J-box attachment after bus bar and tab connection. HelioVolt's unique edge sealant solution is applied for higher moisture resistance. This helps the guarantee of a 25-year lifetime, including in high-humidity environments. Both the encapsulant sheet and low-iron tempered superstrate glass used in lamination have high optical transparency to improve

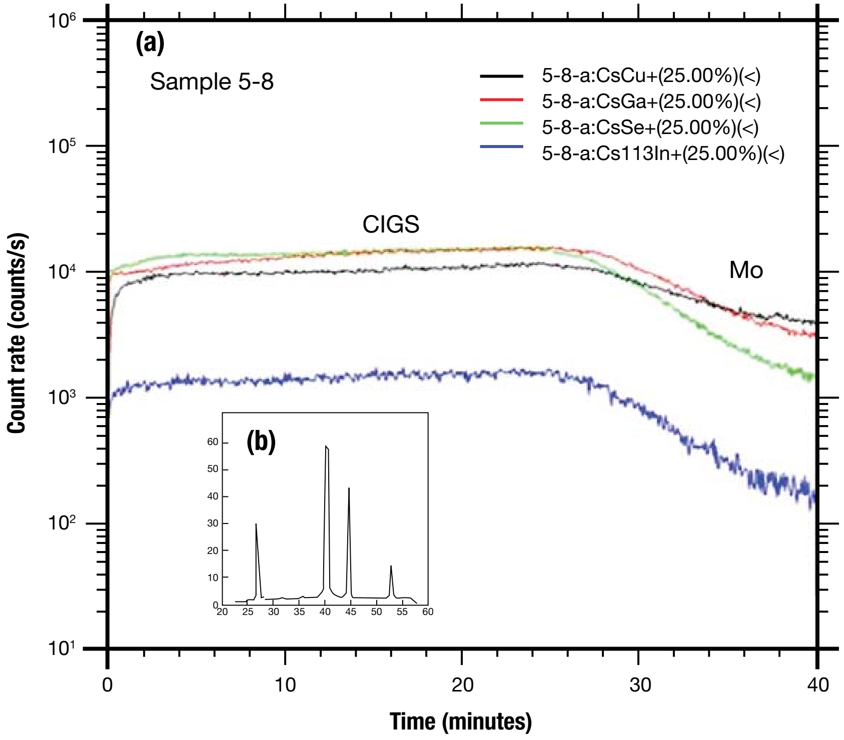

Figure 2 – (a) SIMS depth profile of a CIGS film formed by the reactive transfer process; (b) XRD pattern of a CIGS film fabricated by the reactive transfer process.

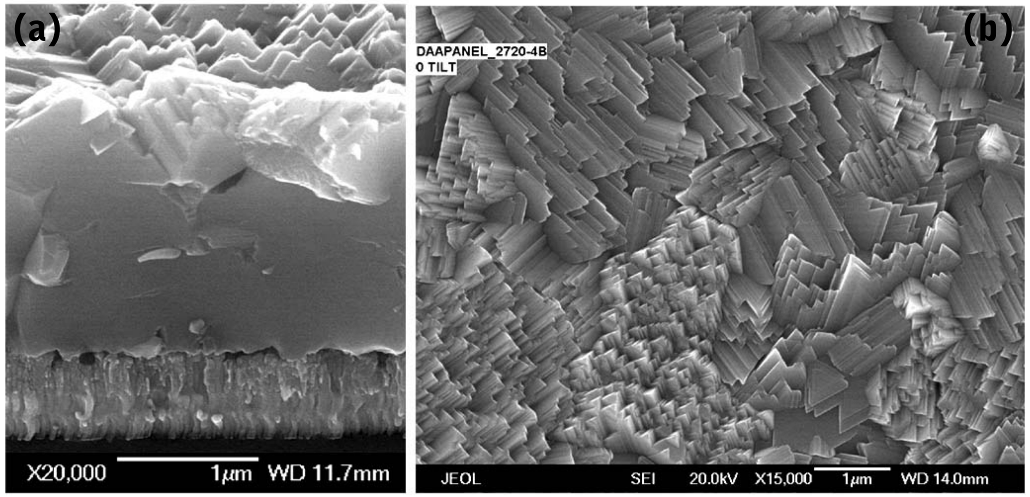

Figure 3 – SEM micrographs showing (a) cross-sectional and (b) top views of CIGS films synthesized in HelioVolt's production line in Austin, Texas.

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photon transmission. Various tests, such as efficiency and wet dielectric measurements, are conducted on every module to ensure good quality control and product safety. Tests such as thermal cycling, damp heat and outdoor module array testing are done on selected samples to ensure exceptional product reliability and performance in the field.

CIGS Formation

The reactive transfer process can synthesize CIGS from the precursors in a matter of several minutes. As we continue to reduce the cycle time, the reaction time can be shortened to seconds. Figure 2(a) shows a secondary ion mass spectroscopy (SIMS) depth profile of a CIGS thin film processed by reactive transfer. The precursors for the film are deposited by PVD. The uniform elemental distribution indicates that a complete reaction of the precursors took place, and the X-ray diffraction (XRD) analysis (see Figure 2(b)) confirms the absence of deleterious phases other than CIGS. All the XRD peaks are based on Mo and chalcopyrite-type CIGS structure, with a preferred 220/204 CIGS orientation. Evidence indicates that 220/204-oriented films may help junction formation and improve solar cell performance.[7] This unique processing approach results in a significantly decreased thermal budget compared with common CIGS manufacturing methods, such as co-evaporation and two-step selenization processes. This advantage leads to higher throughput, and therefore significantly lower cost.

Figure 4 – Photograph of a G2 (120 cm x 60 cm) module produced at HelioVolt's first factory in Austin, Texas (inset: view of HelioVolt's automated manufacturing line).

Figure 3(a) shows a tilted cross-sectional SEM micrograph of a CIGS layer (on Mo) formed with PVD precursors on our production line. High-quality CIGS films with large grains are yielded by the reactive transfer process. Figure 3(b) shows a SEM top view of a CIGS layer in another sample on the production line. The faceted surface enables high efficiency under various lighting conditions.

Device Results and Module Scale-up

Solar cells with a conventional device structure of glass/Mo/CIGS/buffer/TCO were fabricated. The CIGS absorber was fabricated by the reactive transfer process with PVD-based precursors. Cell efficiencies of 14 percent were achieved.[5] With a cell area of 0.66 cm^2, the open-circuit voltage (V_{OC}) was 630.5 mV, the short-circuit current density (J_{SC}) was 30.9 mA/cm^2 and the fill factor was 71.8 percent.

HelioVolt started scaling up its PV technology from the cell level to the module level by first creating a generation 1 (G1) platform for modules. The G1 form factor is 30 cm x 30 cm. With a 14 percent efficiency level achieved in HelioVolt cells, the predicted equivalent efficiency for modules is around 12 percent, if the material quality achieved in a cell is achieved uniformly across the area of the module, with the power loss from 14 percent to 12 percent being mainly due to the non-active interconnect scribes area and to lateral current conduction loss in the finite-resistance TCO layer. Current crowding

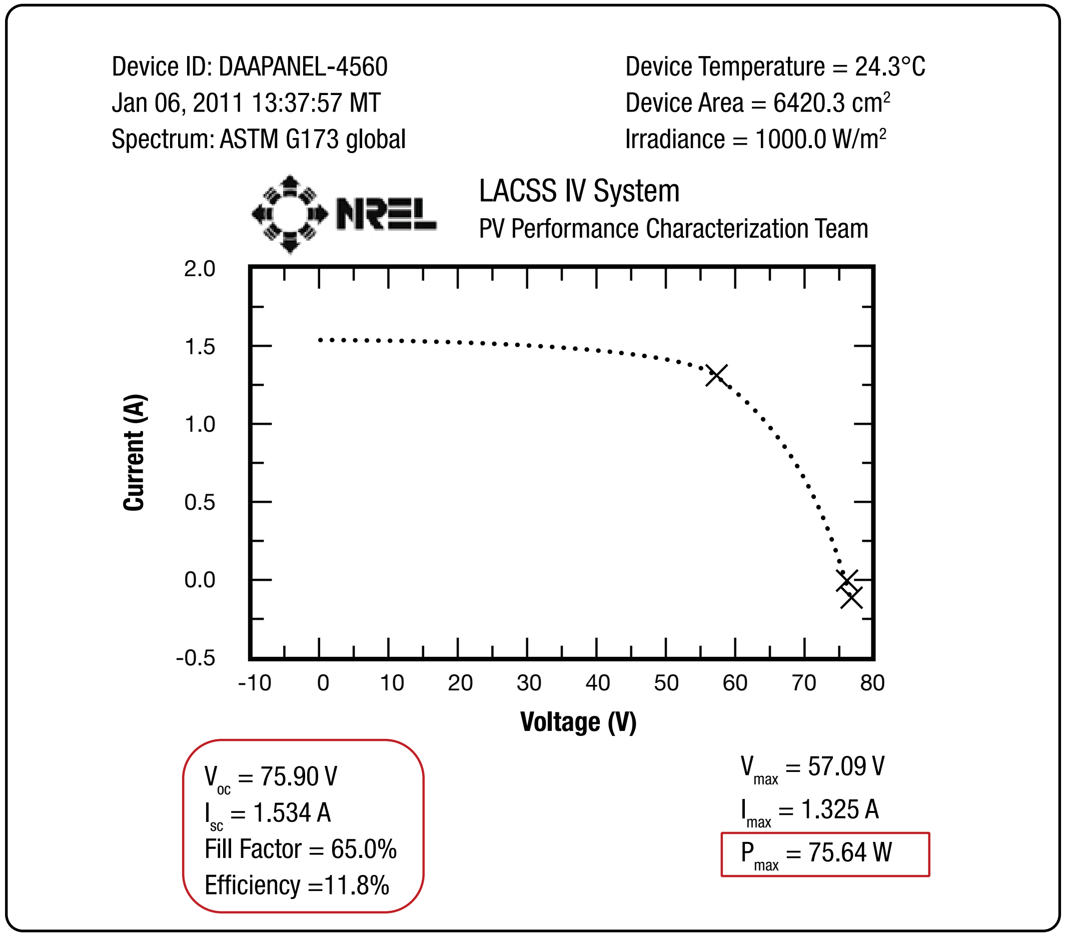

Figure 5 – Light current-voltage (I-V) curve measured by NREL on a HelioVolt G2 (120 cm x 60 cm) module. The efficiency is 11.8±0.6 percent and the output power is 75.64 W.

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within the active segments can also contribute to the power loss, which can be improved by choosing the right segment width based on CIGS and TCO films characteristics. We measured in our G1 modules conversion efficiencies as high as 12.03 percent, and this performance level was independently verified by the National Renewable Energy Laboratory (NREL) at 11.7±0.6 percent efficiency.[5]

The 20 MW manufacturing line at HelioVolt's first factory in Austin, Texas is producing G2 modules, with a form factor of 120 cm x 60 cm. Figure 4 shows one such G2 module, with the inset showing part of the automated manufacturing line at HelioVolt.

During the G2 size module production, it is critical to have good uniformity control in each of the processes and in-line metrology for monitoring. For example, extra attention has been paid to the uniformity of the thickness and composition of the precursor films to avoid deleterious effects on module performance. Heating uniformity, especially at the high temperatures during the reactive transfer, can also be very important to ensure uniform CIGS reaction and avoid glass substrate warpage.

The scale-up to the G2 form factor was successful, with HelioVolt achieving approximately 12 percent module efficiency. NREL confirmed the G2 efficiency at 11.8±0.6 percent, as shown in Figure 5. For this large format module, this high-efficiency level corresponds to an output power of 75.64 W.

Conclusion

HelioVolt's reactive transfer process produces high-quality CIGS films with high uniformity over large areas. CIGS films with large grains on the order of microns are routinely produced, and exhibit optimal crystallographic orientation. Cells with 14 percent efficiency and modules up to 120 cm x 60 cm with 12 percent efficiency are produced with this process. HelioVolt started to commercialize its reactive-transfer-based CIGS technology at its first factory in Austin, Texas.

Acknowledgments

The authors would like to acknowledge the entire HelioVolt team for their contribution in the successful scale-up of the CIGS reactive transfer technology. We would also like to thank Keith Emery and his team at NREL for the verification testing.

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☞Click here to return to Table of Contents

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<< PREVIOUS PAGE | NEXT PAGE >>

Brave Steps Needed in Thin Film Silicon R&D to Harvest Optimal Technology

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Photovoltaic research consultant

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When Applied Materials announced the discontinuation of their product Sunfab™, a fully integrated line for manufacturing thin film silicon solar panels, many took this as a clear signal that thin film silicon is not a viable technology. According to analysts, the material to work with is CIGS (new material that promises high efficiencies) and crystalline silicon (mature and dominant market share). CdTe is doing fine anyhow. While there are surely some facts that support this analysis, it is time to see if all facts are considered and to look at thin film silicon more closely.

Now is the post-hype time for thin film silicon. The hype was created by the prominent battle between Swiss Oerlikon and U.S. Applied Materials on market shares and intellectual property. Both companies achieved considerable sales volume of half- and fully integrated manufacturing lines between 2006 and 2008. Both companies have sold none to little volumes in the recent past, which was considered a first signal of potential failure of thin film silicon. In July 2010, the discontinuation of Applied Materials' Sunfab™ was announced. For many in PV, this marks the apparent failure of thin film silicon. But is this based on a thorough analysis?

Let us look at the press release from Applied Materials: http://www.appliedmaterials.com/news/articles/applied-materials-announces-restructuring-energy-and-environmental-solutions-segment). The only words that are usually looked at are:

"As part of the restructuring, Applied will discontinue sales to new customers of its SunFab™ fully-integrated lines for manufacturing thin film solar panels … ."

Most readers never made it to the following words:

"Applied … will offer individual tools for sale to thin film solar manufacturers, including chemical vapor deposition (CVD) and physical vapor deposition (PVD) equipment. … The company will support existing SunFab customers with services, upgrades and capacity increases through its Applied Global Services segment."

Just as important is this:

"R&D efforts to improve thin film panel efficiency and high-productivity deposition will continue."

Applied Materials was not happy with the drop in sales, so it was just a matter of time when the management had to cut back on efforts and with that, on expenses. But single-tool sales continue; most importantly, the sales of the PECVD tool that forms the heart of a thin film silicon production line. In fact, most of the other tools in the Sunfab™ manufacturing line were supplied by OEMs anyway. The stated continuation on R&D efforts, even if on a smaller scale, also underscores that Applied Materials sees a future potential in thin film silicon.

This potential was confirmed impressively by Applied Materials and many other companies and research institutes at the most recent European PV trade fair and technical conference, held in Valencia (EU PVSEC 25) in September 2010. Basically, all major thin film silicon PV labs and companies presented significant progress on efficiency and commercialization. Oerlikon made the strongest claim, with the launch of their newest manufacturing line, called ThinFab, which apparently allows production costs of 50 € cents/Wp at 10 percent total area panel efficiency (http://www.oerlikon.com/solar/thinfab/). Operation of a ThinFab could start in mid-2012. This clearly challenges First Solar's cost target of 52-63 $ cents/Wp in 2014, as presented by First Solar at the same conference. Oerlikon representatives claim that their cost calculation method is equivalent to the one done by First Solar. So when the cost potential of thin film silicon is challenged, there are answers. According to a press release from Oerlikon dated February 22, 2011, Dong Xu Ltd. is convinced of the competitiveness.

With that, the situation at the two most prominent tool and manufacturing line suppliers – Applied Materials and Oerlikon – is described. When it comes to panel manufacturing, the companies with longest track records and the leaders in volume and technology are Uni-Solar, Sharp and Kaneka. All three panel manufacturers had been around well before Applied Materials and Oerlikon entered the business; hence, they do not rely on Applied Materials and Oerlikon. This fact clearly states that the ups and downs at Applied Materials and Oerlikon do not fully represent the situation of thin film silicon.

The picture of thin film silicon becomes quite interesting when we look at the situation at Sharp. Sharp started R&D on solar cells in 1959. Work on thin film silicon started in 1983. Sharp is one of the top players in crystalline silicon and has reached efficiencies of more than 35 percent with a compound solar cell. Sharp began operation of its Japanese thin film silicon fab with an initial capacity of 160 MW in March 2010 (http://www.sharp-world.com/corporate/news/100329.html). Sharp will also start the production of thin film silicon panels in Italy in the second half of 2011, with an initial capacity of 160 MW. Plans include an expansion to 480 MW (http://sharp-world.com/corporate/news/100802_2.html). When questioned if Sharp sees a certain pressure on sales after all the bad press on thin film silicon, a Sharp representative during the Solar Power International trade show in October 2010 in Los Angeles pointed to a massive poster showing a utility-scale PV power plant using thin film silicon panels. The Sharp representative firmly stated that the

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discussions about thin film silicon have not altered Sharp's business, that Sharp's choice for utility-scale plants is thin film silicon and that the sales volume is well above production volume. In summary, for Sharp, a global technology company with a long history in PV, thin film silicon plays an important role for its future expansion strategy. However, the recent announcement that Sharp will use part of its Sakai operations for back-contact c-Si cells clearly shows that Sharp also sees the challenge with thin film silicon.

What could be the reasons for Sharp or Inventux to continue with thin film silicon? There are several key aspects that need to be fulfilled by any PV technology to reach grid parity in a sustainable way:

1. Environmentally friendly along the whole supply chain (from mining of the resources to the end-of-life of the panel)
2. High availability of resources and/or minimized material consumption to allow scaling and low material cost volatility
3. High inherent long-term reliability
4. High performance ratio (kWh/kW at a specific site)
5. Good aesthetics
6. Fit between PV technology and targeted application
7. High efficiency now and high future efficiency potential
8. Low production costs now and high future cost-reduction potential

In order to make a sound technology choice, all items need to be analyzed and weighted both for the present and for the future. It could be that Sharp and other thin film manufacturers have not only looked at item 7 – the present efficiency level in most productions worldwide is 8-10 percent. Instead, the high availability and minimum usage of silicon, the non-toxicity and the inherent long-term stability of silicon might have played an important role. The often-criticized usage of NF3 for PECVD chamber cleaning can be avoided by using fluorine. The high-performance ratio of thin film silicon is studied by many and will be promoted even more strongly in the future (see, e.g., the agenda of the 3rd Thin Film Solar Summit Europe, March 3-4, 2011, Berlin).

Even if the "softer" items 1-6 listed above might have played the decisive role for the technology choice for the present players in thin film silicon, the efficiency and cost-per-watt challenge needs to be tackled for thin film silicon. In the present situation, fulfilling announced targets is key to regain trust outside the thin film silicon community. Oerlikon has made big claims with its new product ThinFab. It will be interesting to see whether Oerlikon can compete with other thin film turnkey suppliers such as Manz and Centrotherm for CIGS or Roth & Rau for CdTe. Similarly interesting to see will be the outcome of Applied Material's efforts to improve efficiency and productivity. The more-focused-since-downsized activity, in combination with no new turnkey business in parallel and less-global attention, might even help the Applied Material team to gain momentum in specific areas. Sharp's goal announced in 2008 to gradually move toward 1 GW is still in the mind of many industry experts (http://www.sharp-world.com/corporate/news/080327.html). Together with Kaneka (Sharp's long-term Japanese rivals in this technology), and Schüco (the new German heavyweight after buying Sunfilm's two sunfabs), Sharp will be the leader in this technology. The speed at which Sharp will take these steps will be regarded as the equivalent for the confidence level of Sharp in thin film silicon from a technological as well as from a marketing point of view. All players will need to take brave steps to upgrade their existing lines to eliminate unexpected bottlenecks and upgrades to close the gap in efficiency and/or costs to CdTe, CIGS and, of course, crystalline silicon. The steps will take some courage due to the instable political framework of this industry and large oversupply. Future expansion, essential to cut down on overhead costs, will take additional R&D budget up front to develop the next product generation. This would be facilitated by high-risk R&D work at the public level. For that, policymakers will need to be convinced that R&D projects for thin film silicon are worth being funded. In order to improve competitiveness, the thin film silicon community might have to move closer together to share funds and resources and align on a common road map.

The other large element that is left out of many people's minds is the fact that the PV industry is still relatively young, especially when viewed as a consumer-based business. Most people in the industry are still struggling to think beyond solar farms and cannot see how solar technologies can be used in diverse and unique environments such as mobile applications (backpacks, portable power generation), novel ideas such as the solar roadway and the various forms of building-integrated PV technologies (roof tiles, 6 square-meter building facade elements as offered by Schüco, etc.). All can have an impact on the development of differing PV technologies like thin film Si, as each has its own unique needs, and it's doubtless some of those will be very price- or volume-sensitive, which could give thin film Si an edge. The bottom line is that PV technologies change very fast. One minute polycrystalline silicon is in short supply and so is expensive; the next it's the opposite. Raw silicon costs were the reason for the interest in thin film Si but were also responsible for the shine wearing off; however, whenever there is a specific cost of materials issue, such as could be the case with c-Si and the elements of CIGS/CdTe, thin film Si will come to prominence. So don't write this thin-film Si off just yet, as you could regret it.

Times have changed radically, no doubt. The hype that was initially triggered by the entry of Applied Materials and Oerlikon, in addition to PV panel undersupply and high silicon feedstock prices, is finally over. Stakeholders in the thin film silicon industry will now need to show more results with less funding, but that's no different than the teething troubles of many technologies. At the EU PVSEC 25th conference in Valencia, many promising results were presented and many presenters promised even better results in the future. We as an industry need to give them more time to allow for a new phase in the evolution of thin film silicon to progress. ■

ABOUT THE AUTHOR

Torsten Brammer – See page 7

☞Click here to return to Table of Contents

PRINT this article   E-MAIL this article

<< PREVIOUS PAGE | NEXT PAGE >>

Click here to return to Table of Contents | PRINT this article | E-MAIL this article

Craig Hunter
Vice President and General Manager
Clean Energy Technologies, Intermolecular

The PV industry has for some years been hoping for better solutions to the vexing and expensive problem of making contact to crystalline silicon solar cells. The materials, equipment and process involved in screen-printing contacts impact virtually every element of solar cell cost and performance – conversion efficiency (in several ways, including fill factor and effective collection area/shadowing), mechanical and electrical yields, wafer thickness, capital and material cost. Needless to say, there are enormous efforts afoot to improve every element of screen-printing contacts – lower-cost materials, materials that make contact to lightly doped emitters, tools that print narrower or higher-aspect ratio lines (i.e., double printing), to name just a few.

While many industry participants debate “revolution vs. evolution” in solar cell materials and architectures, the same debate can be waged regarding specific process steps in standard cells. For the “evolutionary” crystalline silicon roadmap, what specific tools and processes will prevail in texturing, diffusion, passivation, metalization – continuously improved standard tools and processes, or something completely different?

The claims being made by newcomer Xjet, which offers inkjet tools and inks, are aggressive indeed – lower capital costs, half the materials usage, higher conversion efficiencies (narrower lines, ability to tailor materials specifically for seed layers vs. bulk), thin-wafer enabling and portable to back-contact cell designs.

With pilot tools reported to be in the field already, we will be waiting with baited breath for updates in the coming months and years on this intriguing potential breakthrough in crystalline silicon metalization.

Click here to return to Table of Contents

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Generating Energy for PV-Specific Standards

For the global photovoltaic (PV) power industry to prosper, it must become more competitive with the cost of traditional electric power. That means reducing the cost per kilowatt-hour (kWh) associated with solar-generated power to a level that yields grid parity between solar power and traditional electricity.

Among the factors that weigh on the PV industry's ability to achieve grid parity are standards that add to the total cost per kWh. Following standards is a preferred practice as specifications ensure quality in components, processes, manufacturing and end-product performance.

However, in some cases, PV standards may be stricter than what is necessary to ensure the safe, efficient generation of power. By their nature, tighter specs are more costly. As PV energy producers and market suppliers work toward reducing costs, they need to examine existing standards and determine if less stringent specifications can yield acceptable results while saving money.

Swagelok is addressing one such area of PV manufacturing that defines specifications for stainless steel components used in the production of solar cells. The new Swagelok Photovoltaic Process Specification (SC-06) is the photovoltaic industry's first specification for processing stainless steel fluid system components. It's based on our work in the industry, and continues Swagelok's leadership in process-specific cleaning, which began in the 1980s with ultrahigh-purity components.

With Swagelok SC-06, you can now specify fluid system components with cleanliness and purity levels that closely match the true process requirements for solar cell production. Products processed with SC-06 bridge the gap between ultrahigh-purity standards and the more limited requirements of general industry products. Applied to gas handling components in your system, this specification is designed to help lower overall cost of system ownership. All with the peace of mind that comes with the quality and reliability of Swagelok® products. Using SC-06, our customers take one step closer to grid parity.

To learn more about Swagelok SC-06 and applicable products, visit: www.swagelok.com/solar

Swagelok Company supports the global semiconductor marketplace with skilled associates, cutting-edge fluid system technology, and high-purity and ultrahigh-purity manufacturing operations. The company's manufacturing, research, technical support, and distribution facilities support a global network of more than 200 authorized sales and service centers in 57 countries. A wholly owned subsidiary of Swagelok Company, Swagelok Semiconductor Services Company (SSSC) facilitates a focus on industry needs.

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<< PREVIOUS PAGE | NEXT PAGE >>

Xjet's *FabGrade* Inkjet for Solar Cell Metalization

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Abstract

Xjet develops and manufactures inkjet production printers and inks for solar cell metalization. The company's design overcomes inherent inkjet drawbacks and is covered by over 20 patents and pending patents.

Metalization is becoming too expensive. The rapid decline in $/watt price versus the spiraling price of metal has blown metalization out of proportion. Its cost as a percentage of c-Si cell price has rocketed from 3 percent in 2008 to 12 percent in 2010 (normalized for efficiency). Photon Consulting recently published a forecast for a continued decline in cell pricing from the present $1.2/watt to $0.7/watt by the end of 2012. Even under the unlikely assumption of a freeze in raw metals price, the decline in cell price alone would drive the cost of metalization to an unacceptable 20 percent of the cell price.

Metalization must advance quickly and its cost must be cut in half. New solutions must consider the use of lower-cost metals and a decrease in the quantity of metal. Lowering the capital cost of metalization equipment would also be beneficial.

Boosting efficiency through double print adds 30 percent more metal per cell, but fails to provide a return, as it adds metal when it should be reducing metal. New-generation pastes demonstrate an improved contact on high-sheet rho wafers, but they also require about 30 percent more metal, with fingers as tall as 35 microns. In addition, despite reduced silicon prices, wafer costs still represent about 65 percent of the cell price, forcing the industry to renew its pursuit of wafer thinning. Double print adds substantial mechanical pressure to the wafers and does not support this trend for thinner wafers.

Consuming less than half the metal and printing 35 micron features without making contact, Xjet's inkjet technology provides a solution to cut metalization costs by about 40 percent. Over the past 12 months, Xjet has demonstrated consistent output of 18.8 percent average efficiency and 19.2 percent best cells on production floors. Recent development has shown an 80 percent fill factor with Xjet's full inkjet front metalization solution. Xjet is demonstrating printing speeds above 20 cm per second, which translates to a throughput of 5,000 wafers per hour. Moreover, this inkjet solution includes multiple metals in one printing step, enabling a transition to lower-cost metals. Xjet's front-side metalization printing consists of three types of inks in one path: fritted silver for seed; pure silver on top; and a low-cost bus bar metal providing superior adhesion at a lower cost. In the future, additional metals may easily be added onto this single printer to further reduce costs by layering multiple metals on top of each other.

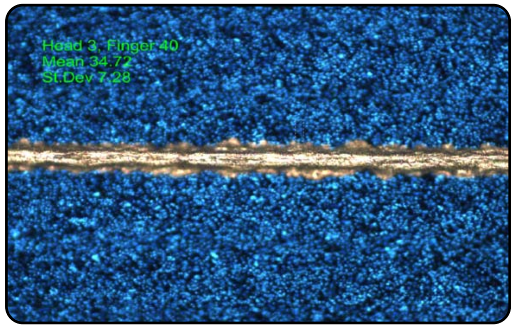
The company is now developing back-contact pastes. Xjet's printers are upgradable to back-side printing at minimal cost. Producing front and back metalization on an inkjet printer in a single step will reduce capital costs for the cell producer by close to 50 percent and become a strong driver for thinner wafers and further cost reduction.

Inkjet technology has been long envisioned as the industry's "silver bullet." On paper, inkjet has all that is required to become the industry's leading deposition tool – much lower cost than photolithography, an additive process eliminating the material waste of spin coating and contactless printing, unlike the wafer-cracking squeegee used in screen printing. In addition, inkjet "counts" and deposits nano-droplets, ensuring very high uniformity across the substrate as well as substrate-to-substrate.

A Bicycle Chain, Printed on Objet's 3D Inkjet Printer

From a mass production perspective, inkjet is a much safer investment than other exotic deposition strategies being proposed and promoted. Inkjet is a commonplace, mature industry and technology. Each year, hundreds of millions of dollars are invested by world-leading companies such as Epson, HP, Ricoh, Konica Minolta, Fuji and many others in the development and production of more reliable, precise and lower-cost inkjet heads. The graphic arts market drives these demands and provides the PV industry a "free," fully subsidized and guaranteed roadmap for better, finer inkjet heads.

Xjet intends to transform inkjet technology from industrial grade for short-runs to fabrication-grade technology for 24/7 production. Starting some 20 years ago with HP Scitex (formerly Idanit), a world-leader in inkjet printing of billboards, the Idanit printer completed a 3.5 x 1.6 meter poster in less than 45 seconds. A few years later, Objet, a 3D inkjet printer for rapid prototyping, was launched. Using UV curable polymers, this innovative inkjet printer converts CAD images to colorful plastic objects within minutes.



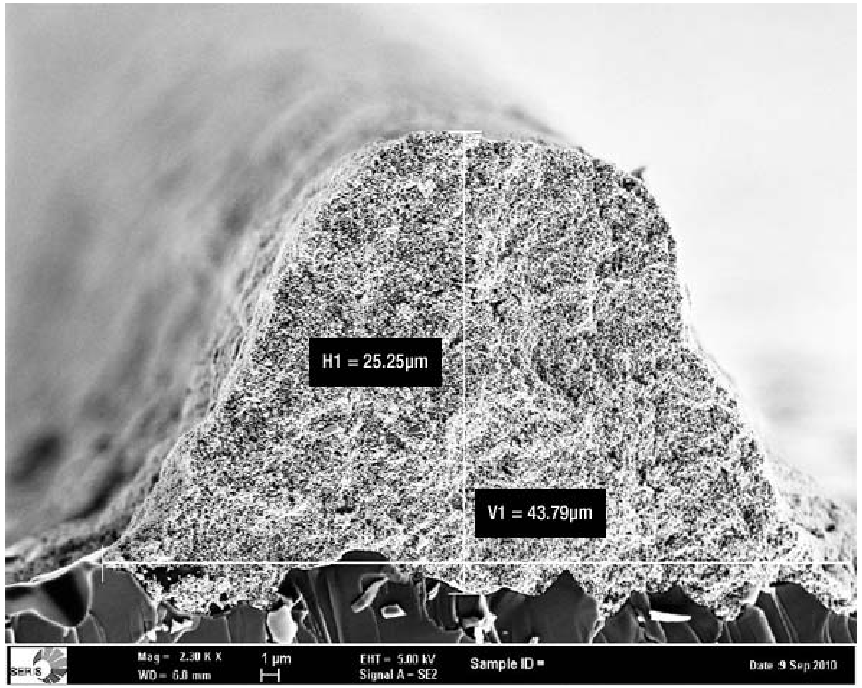
Xjet Printed Seed Layer, 35 Microns Wide, With 25 Microns Core

<< PREVIOUS PAGE | NEXT PAGE >>

Objet, like Idanit, soon became a market leader in its field.

In these two companies, with thousands of installed printers and multiple innovations, inkjet was driven further than what was deemed possible. The next major challenge was to develop the fastest, most reliable inkjet possible. Newcomers to inkjet may assume that investment in ink-to-head compatibility will eventually yield a solution to known inkjet deficiencies such as clogged and misfiring nozzles. This is incorrect, as heads will always clog and inks will never be good enough. Unlike inkjetting wax (used for masking), which is the easiest material to inkjet, direct metalization is much more difficult to implement. Inkjet experts can quickly compute that given the pattern, drop volume and deposition rate required for metalization, hundreds of inkjet heads, operating simultaneously, are required to meet industry standards. An additional challenge is to jet droplets with abrasive and heavy materials (glass frits and silver) with a precision of 5 microns.

Even a home showerhead, jetting water from relatively big nozzles, gets clogged and nozzles stray fairly quickly. Water is the equivalent of wax or aqueous solutions in inkjet. Now think of jetting cement through your showerhead – how long would it take the showerhead to clog and fire astray? In the PV world, the equivalent of cement is metal and the equivalent of the showerhead is the 100,000 30-micron diameter nozzle array. With hundreds of inkjet heads and over 100,000 nozzles firing 10,000 droplets per second per nozzle, all registered to 5 micron accuracy, one begins to understand the challenges Xjet had to overcome.



Xjet-Printed Full Conductor Layer, 43 microns Wide, 25 microns High

Source: Solar Energy Research Institute of Singapore, 2010

Companies have tried to integrate inkjets in LCD or RFID for almost two decades. They were rarely successful in a demanding, production environment. Without the *FabGrade* qualities, which address the problematic clogging and poor repeatability of inkjets, it is hard to imagine how inkjet could be adapted to the demanding fab (cell production) environment.

Xjet's *FabGrade* inkjet prints wafer after wafer at high speed with sub-50 micron lines and a high degree of uniformity. Every droplet is measured and every nozzle is tracked by the system in real time to shut off automatically if clogged or firing stray. Inkjet heads are automatically cleaned and maintained. A metrology system measures finger widths in real time and automatically selects the best nozzles to jet as narrow fingers as possible.

Each connector and plug on the printer is monitored – if one is disconnected, the printer shows when and where this takes place. Every moving part is measured for lifetime expectancy and preventive maintenance. If the system is knocked out of alignment, the printer quickly recalibrates itself.

Similar to screen printing double print, the Xjet printer separates front metalization into two stages – first, a very shallow seed layer achieves a "perfect" contact followed by pure silver on top, for lower resistivity, minimizing the amount of silver consumed. Fraunhofer ISE, Dr. Ebong from Georgia Tech and Xjet have proven in numerous experiments that this metalization architecture ensures good ohmic contact on shallow emitters > 100 ohm/sq., eliminating the need for selective emitters. Efficiency has been proven above 19 percent at customer sites, and research institutes show promise for even higher efficiency to be harvested through further process optimization.

The company highlights that front-grid metalization is just the first stepping-stone, and back-contact patterning with ad- vanced materials is on the company's immediate roadmap. Xjet has already shipped pilot printers to the world's leading cell manufacturers. The company expects to perfect the product through pilot runs in 2011 and be ready for a production ramp-up toward the end of the year. ■

ABOUT THE AUTHOR

Robert Even *is the marketing manager for Xjet. He has over 12 years of high-tech marketing experience with inkjet and automatic inspection capital equipment. Robert holds a B.Eng from McGill University, and an MBA from INSEAD, France.*

☞Click here to return to Table of Contents

PRINT this article
E-MAIL this article

<< PREVIOUS PAGE | NEXT PAGE >>

Click here to return to Table of Contents
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The opportunity for manufacturing control-based cost reduction

Amid the effort to reduce the costs associated with solar energy, there is a golden opportunity to import some of the established principles of manufacturing control from the silicon semiconductor community.

Factory control is highly automated using an integrated computer management system that regulates the flow of wafers through the equipment and tracks each process step. Metrology information is captured with enough detail to determine if the measurement equipment itself is properly calibrated and operating at required specifications. Film thickness, defect location and a variety of additional information are all available for process control, which allows for higher yields and optimum circuit performance.

An integral part of this strategy is the use of advanced equipment control (AEC) and advanced process control (APC). AEC and APC use sensor-based collection of information inside the process equipment to provide real-time monitoring of materials properties and equipment status. This information can be sent forward to the next process step, and software can be utilized to alter the process for optimum results. This information can also be used to correct equipment faults.

The solar industry is introducing similar approaches to manufacturing control. Especially important are correlations between physical and electrical characteristics and yield. As the solar industry works toward improved efficiency and yield, it will be keeping watch over production costs. It will be very interesting to observe the evolution of manufacturing control and the implementation of new metrology.

In this issue, the papers cover topics associated with improved process control. Randhahn and Gritsch discuss the relationship between physical and electrical properties and a new measurement capability known as the Solar Measure I-V Curve Tracer.

Optimizing Approach for Thin Film PV Production

Jean Randhahn,[1] Stefan Gritsch[2]
[1]Dr. Randhahn Solar Engineering
[2]Dr. Schenk GmbH Industriemesstechnik

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Abstract

In current thin film solar manufacturing, module quality and process conditions are primarily determined by physical metrics and the final electrical metrics of the product, the solar module. For established well-known manufacturing processes such as optical disc, this is feasible, as the effects and causes of defects have been thoroughly studied and documented. For TF PV production, however, this is not the case, which leads to several shortcomings in process control and production optimization. This article shows one optimization approach and some of its pitfalls and proposes a quality indicator.

Minimizing Loss Mechanisms

In current thin film solar cell manufacturing, module quality is primarily determined by physical and basic electrical metrics such as layer thickness, resistivity and optical haze. Some sites perform offline spectral response and I-V measurements on special samples. The sampling rate of such offline measurements and their special design often render results unfit for process control though, since they do not necessarily represent the true production process. Additionally, all production lines feature a sun simulator to determine the final module quality in terms of their electrical rating.

The goal for production is to maximize equipment uptime and yield and to stabilize all processes. For all of these steps, the above-mentioned metrology can be sufficient. The next step is raising product quality, which is equal to an increase in power output and the securing of guaranteed product longevity. The decision of how to best achieve this is based on the solar module output, the result of which is obtained in the final electrical test. This final test, which is performed on a (often pulsed light) sun simulator, yields the current-voltage characteristic (I-V curve) of the solar module. Since a PV module comprises many individual cells, this characteristic is the result of the interaction of these individual cells. The interaction between the cells, however, remains invisible to those measurement devices; only their result is detectable. The interaction involves effects such as:

- current limitation due to single defective cells, e.g., deposition irregularities
- current and efficiency gradients over the module due to layer and interface properties

<< PREVIOUS PAGE | NEXT PAGE >>

- shunted cells causing a current drain
- suboptimal working points of cells

Despite the fact that these effects are well-known on the individual cell level from laboratory tests, they are often not observed in production environments due to lack of suitable equipment. Still, it has been readily acknowledged that only the understanding of loss mechanisms in the module will lead to significant performance improvements.[1] Not knowing the interaction on the cell level reduces the potential of power output optimization. Two cases present themselves:

(1) Effects on cell level pass unnoticed and corresponding defects in absorber production are never corrected.
(2) Existing defects seen with other metrology are misinterpreted and lead to either unnoticed quality loss or cost-intensive corrective actions that yield only limited improvement.

One possible solution to this dilemma is the measurement of the I-V curve of every single cell. A few years ago, this might have seemed like a tremendous task; however, there have been many major improvements in sun-simulator-related technologies that simplify this job. Today cell I-V recording systems are able to work inline in a production flow.

Cell I-V Curve Measurement

A common procedure to measure the I-V curve of a cell of any thin film technology is to cut the samples to a standard size of 1 cm^2. In this way, the results for different manufacturers or labs can be compared and side effects are kept to a minimum. Since cell dimensions on PV modules are significantly larger, side effects must be accounted for. This especially includes resistance issues due to limited contact layer resistivity, spectral response (SR) for multi-junction cells, and cell contacting and illumination dependence on module configurations.

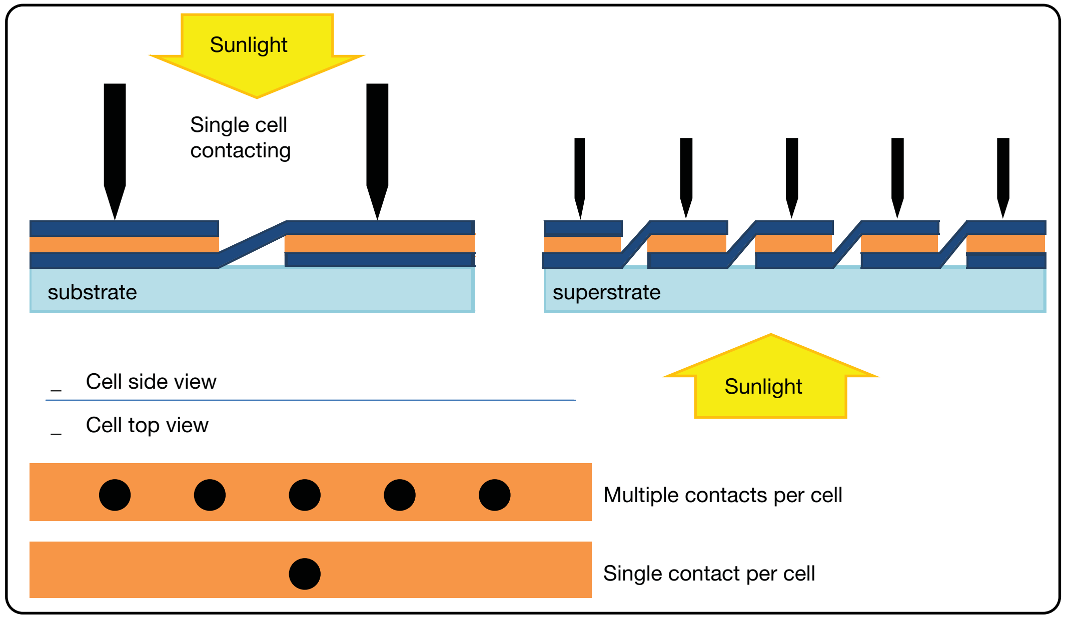

Figure 1 – Substrate and Superstrate Configuration, Single Cell and Cell String Contacting and Single Contact vs. Multiple Contacts Per Cell

Resistance Issue

The most obvious way to contact a single cell of interest on a full module is to use its exposed contact and the exposed contact of the adjacent cell. The latter is connected to the buried contact of the cell of interest (Figure 1). The cell's contact layer then forms the highest resistance in the measurement path. Due to this resistance, the current from a single-point contact over the cell is not uniform, which causes

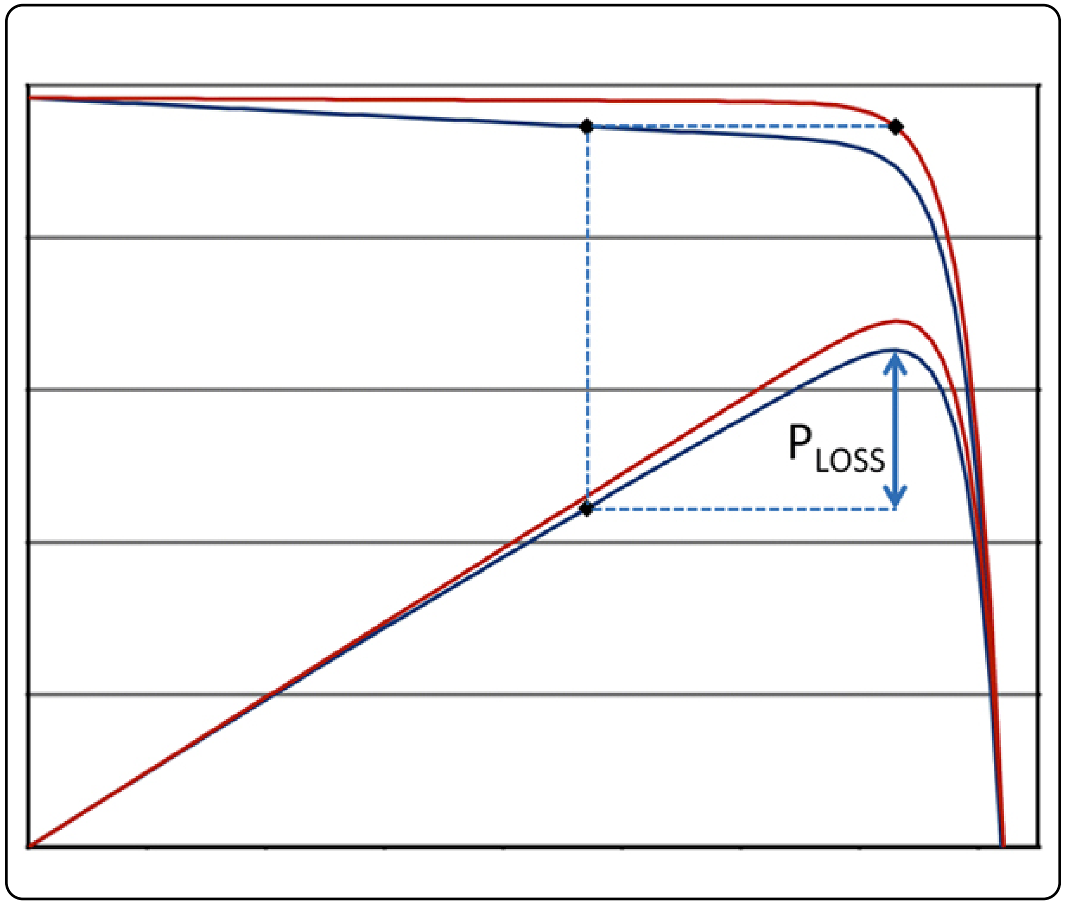

Figure 2 – Two IV-& Power Curves Showing Same ISC and Power Loss Due to Working Point Mismatch

<< PREVIOUS PAGE | NEXT PAGE >>

errors in shunt and serial resistance (R_P, R_S) and therefore in fill factor (FF).

One possible solution is to cut out one or multiple small cells on the module and perform an I-V measurement on them. Although this method delivers reproducible results, it is destructive and only partially representative for the module.

A second solution is to use a (nearly) full cell contact, such as multiple contact pins, which allows current to distribute in the contact pins rather than in the cell's contact layer (Figure 1).

A third solution is to connect multiple cells on the module in series (Figure 1). This allows for a uniform current distribution on all contacted cells except for the first and last ones. This method yields good spatial resolution in combination with multiple contacts.

A fourth way is to establish a model for the occurring error and compensate the deviation in the I-V curve (mainly at R_S and FF). The constant geometry of the cells should yield a consistent behavior. However, R_S and FF are calculated from the non-linear section of the I-V curve and are sensitive to even the smallest changes in illumination and cell performance.

Spectral Response Issue

The goal of the measurement is to check single-cell properties in order to obtain information on cell interaction. A simple semi-monochromatic light source (narrow bandwidth source) is sufficient for this purpose. This can be realized with LED technology that today is far more stable and more readily available than conventional sun simulator light sources. Considering the popular multi-junction cells, multiple weighed semi-monochromatic illuminations are required to obtain single cell information.

Unfortunately, the common rating for continuous spectra illumination (e.g., assuming AM 1.5 G spectrum as in IEC 60904) does not make sense for semi-monochromatic light sources. An alternative solution is the use of a sun equivalent. This presumes a linear correlation between the cell's short circuit current (I_{SC}) and irradiance (G). As I_{SC} can be calculated from the spectral response of a cell (SR(λ)) and the spectral irradiance (G(λ)), a factor k between the theoretical I_{SC} under AM 1.5 G and a semi-monochromatic light source can be computed.

$$I_{SC}^{ref} = \int SR^{cell}(\lambda) \cdot G^{AM1.5G}(\lambda) d\lambda$$

$$I_{SC}^{mono} = \int SR^{cell}(\lambda) \cdot G^{mono}(\lambda) d\lambda$$

$$k = \frac{I_{SC}^{mono}}{I_{SC}^{ref}}$$

This factor k can be interpreted in the following way: the multiple of normed suns that the cell in question sees as being emitted by a semi-monochromatic light source. In this way, multiple light sources become comparable and can be adjusted to enable meaningful data in the I-V measurement of multi-junction cells.

Module Configurations

In present thin film cell technologies, both substrate and superstrate configurations are used (Figure 1). While the superstrate configuration allows for easy access to individual cells, the substrate configuration presents an obstacle in obtaining cell I-V curves (Figure 1). This is because the sunny side is the same side on which the cells are accessible during their production. Substrate configuration is used, for instance, by CIGS technologies. Since regular contacting schemes (e.g., pins) cause partial shading, I-V measurements will always be impaired to a certain degree. Such shading especially influences the parameters I_{SC}, FF and maximum power.

Proposed Quality Indicator

Two factors are taken into account regarding the quality rating of a module and the individual cells: 1) the power output capacity of the cell; and 2) the power output losses due to interaction of the individual cells. The power output capacity is often simplified to the use of the I_{SC} as it is strongly related to many light conversion properties, such as absorber spectral response, light trapping and front-contact spectral window. Power loss due to cell interaction can be seen directly in the power output value. Yet it is not the maximum power point (P_{MPP}) of each cell, but rather the power in the working point (P_{WP}) that is in effect. The reason is that power loss can be caused by driving a good cell into an unbeneficial working point simply because of its series connection with other cells. Therefore, the difference between P_{MPP} and PWP is suggested as a reasonable indicator. The working point value is obtained by using the module's P_{MPP} value and breaking it down to the cells. For example, a module containing a series connection of cells will feature a constant current through all cells on a first approach. This leads to a specific working point for each cell in the module, which does not have to correspond to current at maximum power point (I_{MPP}) (Figure 2). More refined approaches may even take into account the slight deviation from this behavior due to other effects in the cell.

Solar Measure I-V Curve Tracer

Recently, Dr. Schenk GmbH Industriemesstechnik introduced a non-destructive, high-speed metrology system. It is capable of inline I-V curve measurement of each cell in a module.[2] The system integrates solutions for contacting substrate and superstrate configurations with various contact schemes. Its LED light source supports several cell technologies including multi-junction. Due to its LED light source, it is easily tunable in irradiance to conform to the proposed approach using a sun-equivalent factor. The available irradiance adjustment adds the benefit of testing low light behavior. Since the system records full I-V curves for each cell, both homogeneity of cell properties and cell interaction are made visible.

Summary

Production stabilization and quality improvement are ever-ongoing tasks in a production line. As product quality in terms of power output and longevity directly affects product prices, it is of great interest for maximization. One

<< PREVIOUS PAGE | NEXT PAGE >>

approach is to minimize output power losses by understanding cell interaction in the module and tracking power losses to their root causes. Such an approach requires more information than a full module-based sun simulator can yield. A cell I-V measurement is required. Predominant issues in this kind of measurement were shown, and power output in the cell working point was proposed as a quality indicator.

The main benefit of such an approach lies in the reduction of optimization efforts by identifying the most severe causes of power loss and channeling resources into meaningful improvement projects.

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☞Click here to return to Table of Contents

PRINT this article E-MAIL this article

MODULE & PANEL CONSTRUCTION

Click here to return to Table of Contents PRINT this article E-MAIL this article

Bill Richardson
Head of Research & Development, SOLON Corporation

In the PV industry's never-ending quest to compete, the game of wringing cost out of every produced electron is played on many levels: module level, system level, cell level, etc. Sometimes (often) a cost saver on one level leads to a headache on one or more of the others. For example, using thinner cells means lower cost. It also likely means more fragility and consequently, higher breakage rates, a manufacturing headache to be sure. Or is that an opportunity? In the following article, Drs. Kris Baert, Jonathan Govaerts and Jef Poortmans of imec present their proposed elixir to the headache of incorporating ever-thinner silicon cells into modules.

Their "i-module" (interconnect module) concept involves replacing standard tabbing and stringing of back-contact cells with a more integrated metalization technique. In essence, cells are adhered front-side down to the substrate and then windows are opened in the rear encapsulant through laser ablation. These windows allow for deposition of the metalization. Contacts can then be welded in whatever scheme desired before the final layer of encapsulant and backsheet is added. The theory goes that reduced cell handling results in less breakage, but also that this process allows for easy integration of miniaturized components and potentially increased throughput.

Why stop there though? Taking things one step further results in the – what else – "i^2-module" (integrated interconnect module). In this case, the actual processing of the cell and junction creation is carried out while the wafer is supported on the substrate, which the authors argue should allow for the scaling benefits associated with parallel processing as well as utilization of even thinner cells. They rightly point out that cell sorting would then no longer be possible, but then perhaps we can leave the cure for that particular headache to a future issue.

Encapsulating Thin Cells: The i-module Approach

K. Baert, J. Govaerts, J. Poortmans
imec

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Abstract

A novel approach is proposed for the module encapsulation of thin silicon back-contact solar cells. The concept differs from existing concepts by the fact that cells are mechanically fixed to the module glass prior to interconnection. The approach is compatible with the long-term trend to ultra-thin silicon solar cells and can lead to improved performance and reliability. As a next step in the module roadmap, we envisage an evolution toward module-level fabrication of wafer-based thin silicon solar cells.

Introduction

With crystalline silicon solar cells currently being the most prevalent type of photovoltaic technologies (and for the predictable future), the production cost should still be substantially lowered to get to grid parity and beyond. There are numerous ways to reduce production costs, ranging from lower-temperature processing and cheaper materials to higher-throughput systems and improved efficiencies. Here the idea is to embark on the route toward ever-thinner cells. This serves the purpose of cutting cost by reducing the amount of silicon needed, especially beneficial in view of a predicted shortage of solar-grade silicon in the (near) future.

The current industrial approach for crystalline Si PV-modules consists in processing the individual crystalline Si cells, and then stringing them together into modules. However, according to our own roadmap [1,2] and supported by other roadmaps (see e.g., the CTM-roadmap[3]), back-contacted solar cells made on significantly thinner Si-foils will prevail in Si-PV on the longer term. As a result, the current cell manufacturing and module integration approach will undergo drastic modifications. The first problem to be tackled is wafer breakage – this could be improved by non-contact wafer handling procedures, but today the approach is speculative below 80 µm. More fundamentally, however, warping considerations would severely restrict the process window of most of the process steps – in practice, only virtually stress-free processes would be viable that will be particularly challenging for metalization in particular.

Imec is therefore developing a new module technology for back-contact solar cells, referred to as the i-module (interconnect-module). The concept originates as a novel method for fabricating solar panels starting from < 120 µm thin back-contact crystalline silicon solar cells. This concept is aiming at an improved reliability due to embedding in silicone and interconnection of back-contact solar cells through alternative module-level metalization techniques, as compared to tabbing and stringing of the cells and subsequent lamination in state-of-the-art module manufacturing. Additionally, it can by extension be applied for ultra-thin solar cells whichever way they have been fabricated. Rear-contacted heterojunction solar cells could especially provide here a unique advantage in the sense that the cell process, the inter-cell metalization and embedding of additional components inside the module can be combined in one integrated cell-module-integrated component flow.

Figure 1 gives an overview of the basic process flow of the i-module approach. On a clean glass module substrate, an adhesive layer is applied, and the back-contact solar cells are placed with the front side toward the glass, so that the contacts remain available for processing at the rear. After this, the full area is covered with an encapsulant, so that the

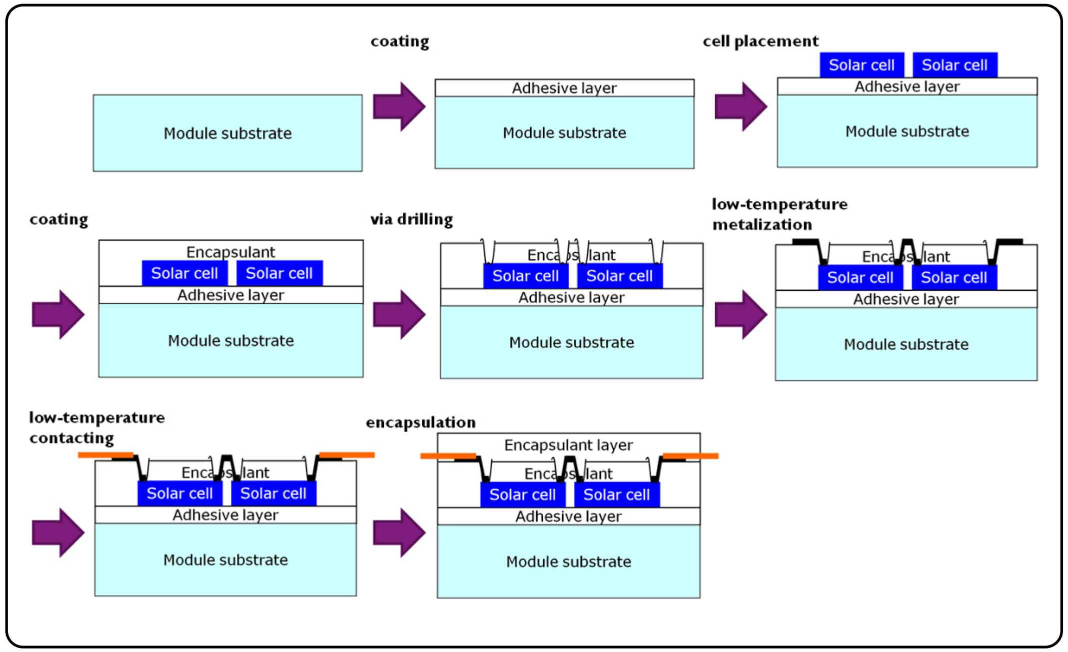

Figure 1 – i-module Process Flow for Back-Contacted Solar Cells

cells are fully embedded. The contacts are then accessed by drilling vias through the encapsulant material, and subsequently depositing the metalization, patterned according to the preferred interconnection scheme for the cells. Outside contacts are provided by welding strings to some designated areas of the metalization, and finally, another layer of encapsulant, possibly in combination with a back sheet, is applied to protect the metalization and reinforce the relatively weak interconnection points.

The potential advantages, as compared to the conventional approach as used in, e.g., the SunPower modules,[4] and the ECN approach,[5] are summarized in Table 1. Wet coating as opposed to dry lamination could result in an increased speed and throughput, and allow for thinner cells, as any uneven pressure distribution during lamination could result in breakage. The use of silicones as adhesive and encapsulant instead of EVA is considered to be beneficial in terms of optical performance [6,7], due to a reduced UV absorption. It is also expected to improve reliability,[8] because of a lower glass transition temperature and Young's modulus, a better UV stability and reduced moisture takeup, and a higher heat and flame resistance, which is interesting from both a processing (e.g., the silicone can withstand soldering temperatures) and safety point of view.

Another distinctive enabler as compared with regular c-Si or thin film modules is that miniaturized chips could be integrated at the cell level and seamlessly interconnected with the PV cells. This allows a seamless integration of miniaturized components that may be a critical feature enabling smart PV modules.[9]

Technology

Coating of the different silicone layers can be done by blade coating, dispensing or screen printing silicones such as Dow Corning's PV6010 Cell Encapsulant. The flow has been developed, at first with dummy cells and several trials, and subsequently demonstrated as proof-of-concept with 2x2 cm^2 functional 120 µm thick interdigitated back-contact cells as well as standard thickness MWT cells.[10] CO$_2$ laser drilling was used to ablate vias to the contacts of the embedded cell. For interconnection, feasibility (as proof-of-concept) was proven through either industrially compatible ribbon soldering for

State-of-the-Art SunPower	ECN	imec i-module	Potential Advantages
Dry lamination	Dry lamination	Wet coating	• Speed, throughput • Thin cell capability
EVA foils	EVA foils	Silicones	• Optical performance • Reliability
Stand-alone cell-to-cell soldering (tabbing/stringing)	Module-level interconnection (conductive foil and adhesives)	Module-level interconnection (soldering, plating)	• Reduced cell-level handling/processing (breakage) • Thin cell capability

Table 1 – Summary of Comparison of the i-module Approach Against Other Module Manufacturing Approaches for Back-Contact Solar Cells

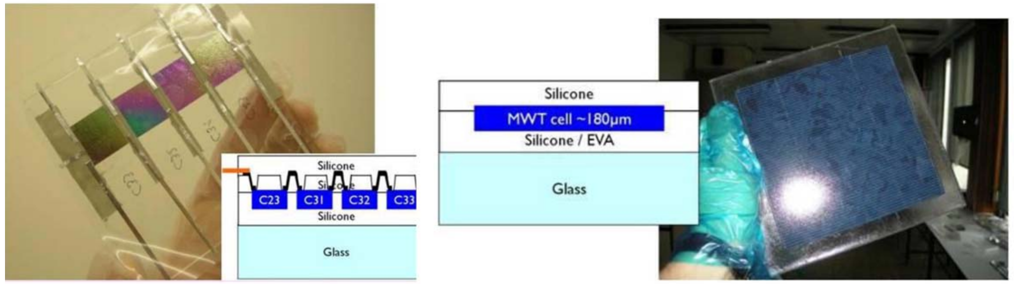

Figure 2 – View of experimental i-modules. Four small-area back-contact solar cells[11] with a thickness of 120 µm are embedded in a mini-module (left); industrial MWT cells[12] are embedded in 1-cell-modules for reliability testing.[10]

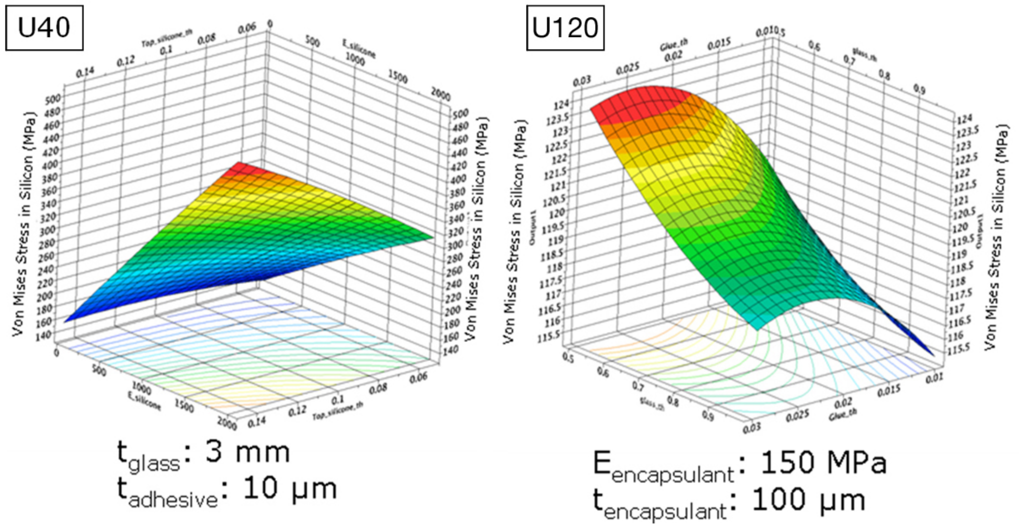

Figure 3 – Example of Stress Simulation in a 40 µm Resp.; 120 µm Crystalline Si Solar Cell as a Function of Glass Thickness and the Embedding Glue Thickness[13]

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industrial MWT (metalization wrap-through) cells, or low-temperature Ag paste for next-generation IBC (interdigitated back-contact) cells. For bringing out the module power, outside contacts were incorporated by contact welding standard Sn-coated Cu tabbing strings. Initial experiments have resulted in functional modules with small-area 120 µm thin back-contact cells, and preliminary outdoor tests are promising. Some impressions of the final result are given in Figure 2, showing the interconnection of four cells resulting in a module efficiency of 16.1 percent with relatively low loss as compared to the efficiency of the original rear-contacted cells.

Longer term, we are looking toward electroplating of Cu. The reasoning behind this is threefold. First, such a type of interconnection could be integrated with the cell metalization, as discussed further in the i^2-module concept. The second consideration would be the improved conductivity of bulk Cu (typically also used for the ribbons in standard module technology) versus screen-printed Ag. Thirdly (though not less important), Cu is considered to be a more sustainable option compared to Ag, which will probably also translate into a cost advantage in the longer run.[14] Cu plating has also been demonstrated already for PERC-style solar cells.[15]

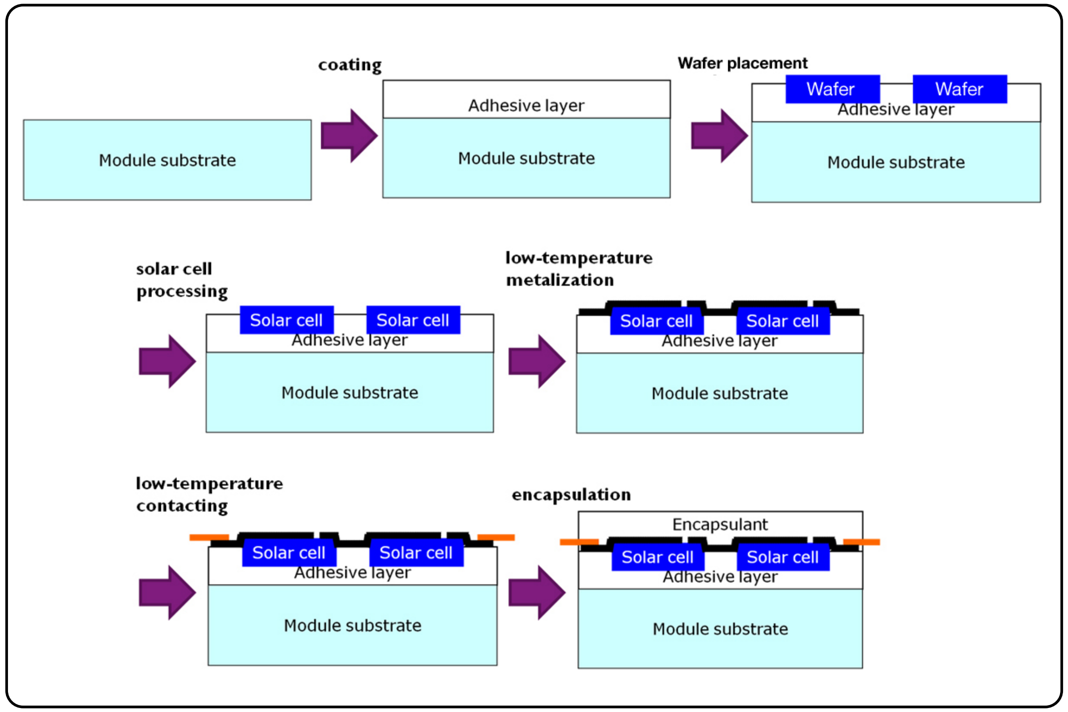

Figure 4 – i^2-module Process Flow

Reliability

Concerning reliability, initial steps have been taken toward predicting failures in modules based on i-module technology. Starting from a so-called failure mode and effect analysis (FMEA), the issues most likely to occur in the module are related to cracking of the cells, cracking of the interconnections and delamination of the silicone layers. To predict these possible issues, simulations of a module model are very helpful: By using finite element modeling, stresses and strains in the different layers may be predicted. If these values are compared to the material parameters (silicon yield strength, metalization strength and silicone adhesion peel strength), this gives a good indication of possible problematic areas in the module. As an example, Figure 3 shows the stress in the silicon cell as a function of the thickness of the glass, adhesive and of the encapsulant layer, and as depending on Young's modulus of the silicone. In this example, it seems that stress in the silicon is minimized by using thin silicone layers, silicone with a low Young's modulus, and a thick glass substrate. Another outcome of the modeling applicability is the analysis of strain in the silicone (which might lead to delamination at the sides during thermal cycling) or the strain in the Cu interconnect bridges between adjacent cells (which might lead to failure by fatigue).[16]

i^2-module

The i^2-module approach (for integrated interconnect-module), aims at carrying out cell processing as much as possible on module level. In this concept, the cells are fixed to the glass superstrate as soon as possible; so, after front-side processing at cell level (which must be done either stand-alone or using carrier substrates). Then the junction is created at the (still-accessible) back of the wafer, and base and emitter regions are contacted, at the same time also providing an electrical interconnection between the neighboring cells. The conceptual flow is shown in Figure 4.

Two main advantages can be identified for such a flow compared to conventional crystalline Si module manufacturing, where cells are first fabricated and only then integrated into the module. The first one encompasses all the scaling benefits that may be associated with parallel instead of serial processing: throughput, cost, etc. The second one is that it offers the possibility of processing much thinner cells: As they are supported during processing by the module substrate, the breakage can be expected to be significantly lower, with anticipated higher yields (we previously already demonstrated embedding of 40-micron-thin foils[17]). The critical point for such an approach is the fact that post-process cell sorting is no longer possible, such that the (uniformity) requirements for the (larger-area) equipment will need to be even more stringent compared to stand-alone cell processing equipment.

This i^2-module approach is targeting an a-Si heterojunction IBC (interdigitated back-contact) structure, as the a-Si heterojunction has a proven potential for high efficiency [18] and is compatible with processing at low temperatures

<< PREVIOUS PAGE | NEXT PAGE >>

that is required for the glass and (silicone) adhesive used for fixing the cells to the glass.[10] Development in this concept has up to now mainly been focused on depositions of a-Si by PECVD, and values in the range of 50 fA/cm^2 for the emitter saturation current have already been obtained.

Conclusions and Outlook

We have described our vision on the evolution of back-contacted crystalline Si solar cell modules. The proposed "i-module" concept is based in essence on an embedding technology using back-contacted solar cells that are interconnected on module level. A straightforward extension of the proposed embedding technology allows the integration of additional components and interconnections. A next-generation, even more disruptive concept is the i^2-module, which proposes transferring the majority of the solar cell processing steps from stand-alone wafer to module-level processing.

Endnotes

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ABOUT THE AUTHORS

Kris Baert *obtained his Ph.D. from Leuven University, Belgium, in 1990 on PECVD of thin film c-Si. From 1990 till 1992, he worked on TFT-LCDs with Mitsubishi Electric (Japan). In 1992, Dr. Baert joined imec (Belgium), where he managed research and development in various areas of MEMS and Integrated Microsystems. Since 2008, he has been program manager of silicon solar cells in the SOLO department.*

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☞Click here to return to Table of Contents

PRINT this article   E-MAIL this article

<< PREVIOUS PAGE | NEXT PAGE >>

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VP Product Strategy & Business Development
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The term "photovoltaic system" spans a wide variation. From off-grid to on-grid and from 1 W to 100 MW, the variety of systems and usage is incredible. The implementation of such a system has always included – other than the photovoltaic source – cabling and power electronics to harvest the sun's energy and redirect it to the where it is needed: the load.

In the last several years, we have seen a rapid evolution and revolution in the way PV systems are implemented. The balance-of-system (BoS) developers – driven by the constant need to increase performance and improve financial gain – have introduced new concepts, methods and components to the PV systems.

This evolution is also gaining from the latest developments in power semiconductors and components such as new control schemes based on digital processing and new switching elements and materials, among which we can count vertical FETs, SiC and GaN. To these we can add the leapfrog advances in energy storage devices, initially driven by commercial mobile devices, and lately by the automobile industry.

The following article describes "independently integrated solar products (I^{2}SP)," which utilizes the advancement made in technology, as described above, to offer smaller, more integrated and more sophisticated photovoltaic off-grid products to the modern environment.

A Simpler BOS = A Faster ROI

Fannon Lim
Solar Research Pte Ltd., Luna Road LLC

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The words "solar energy" and "solar power" convey the thoughts of relatively medium- to large-scale projects and installations; however, through the use of creativity and innovation, we are now able to integrate the same concept of solar energy into smaller products that may have even bigger applications and impacts around the globe.

Quite often, when people think of using solar to generate power for lighting applications or other usages, the thoughts of huge rooftop spaces or lands are required to house the photovoltaic (PV) energy system. This is particularly true if the user is thinking of harnessing the sun's energy to power electronic devices inside the building that all possess high power consumption and demands. However, if such a system is set up to power outdoor devices, it is not as economically attractive as using "independently integrated solar products."

Independently integrated solar products (I^{2}SP) are products that are innovatively designed to be stand-alone solar product solutions fulfilling a specific need. These products can work independently and are completely modular. They have a much simpler "balance of system" (BOS).

A complete PV energy system typically comprises three subsystems:

1) On the power-generation side, a subsystem of PV devices (cells, modules and arrays) that converts sunlight to direct-current (DC) electricity.
2) On the power-use side, the subsystem consists mainly of the load, which is the application of the PV electricity.
3) Between these two, we need a third subsystem that enables the PV-generated electricity to be properly applied to the load. This third subsystem is often called the BOS.

The BOS typically consists of structures for mounting the PV arrays or modules and the power-conditioning equipment that adjusts and converts the DC electricity to the proper form and magnitude required by an alternating-current (AC) load. The BOS can also include storage devices, such as batteries, so that the PV-generated electricity can be used during cloudy days and at night to charge controllers that regulate the power being transferred from the solar panels to the batteries.

<< PREVIOUS PAGE | NEXT PAGE >>

Compared to a PV system, the BOS for I²SP is simpler. An I²SP also consists of a solar panel and a load, but the BOS does not require a power inverter or structures to mount the PV arrays. All the components are integrated within the product itself, and the product will be able to self-generate electricity and power the load within it. Examples of such products that we have integrated are road markers, street lamps and illuminated signages, which are all installed outdoors as stand-alone systems serving a specific purpose and need.

Figure 1 – Luna Road Markers Illuminating a Private Condominium Driveway

Figure 2 – Luna Eyes Illuminating a Public Walkway

Using a PV system to power outdoor devices such as lighting applications is inefficient and ineffective as compared to using I²SP, for the following reasons:

a) I²SP uses DC electricity throughout the BOS, which minimizes losses as compared to using inverters in PV systems.

i.e., The I²SP generates DC electricity that is stored in batteries to power DC loads, such as LED lightings, without inverting the electricity to AC, which will have some losses.

b) Having a PV system on the rooftop or on open land means long cables are required to be routed to power the outdoor devices at different locations. This will usually cause cable losses. To minimize such losses due to voltage drop, the simplest and most obvious way is to use larger cables, which in turn yields higher costs.

c) Being modular means that I²SP can be added at a later stage as compared to a fixed PV system.

i.e., When a PV system is designed to power 50 lamps, and within a year it is decided that another 20 lamps are required, the PV system may not have enough power generated to power all 70 lamps. However, with I²SP, you can fairly simply add another unit to obtain the extra lighting applications.

Figure 3 – Luna Eyes Illuminating a Floating Bridge With no AC Supply

Figure 4 – Luna Sign – Unlighted (left) vs. Lighted (right) in Daylight

d) Being stand-alone means that I²SP can easily be added conveniently at any location. Often underground cables are laid for the predetermined lamps; to add new lamps at a new location would incur high costs of routing new cables. I²SP can operate individually without any cables at any location.

Another key advantage of integrating solar panels into I²SP is the return on investment (ROI). The ROI for solar becomes more attractive as compared to using PV systems. Currently, a PV system takes typically 10-12 years to break even; however, by using I²SP, the ROI can be as low as two years. This is largely due to a simpler and integrated BOS, where the user will save costs from underground cabling, long cables and lower efficiencies.

With deployments of solar made easier and cheaper from these innovatively designed I²SPs, Luna Road believes in saving lives, protecting and preserving our environment, in addition to beautifying nighttime roads all around the globe. The Luna Road products will deliver safety, beauty and eco-friendliness wherever they are installed. The future of nighttime illumination is here! ■

About the Author

Fannon Lim *received his Ph.D. and B. Eng. degrees from the University of Glasgow in 2003 and 1999, respectively. His interest in entrepreneurship and green energy led him to join Solar Research as chief operating officer, and head the Asia headquarters of Luna Road in Singapore.*

☞Click here to return to Table of Contents

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<< PREVIOUS PAGE