



Wednesday at PVSC42 began early for the most active attendees with the Sun Run taking place. Lots of participants got to see New Orleans while enjoying a morning constitutional. Many stiff limbs for the rest of the day, but also some very big smiles. To the right can be seen the brave souls led by the indefatigable Larry Kazmerski.



When things got under way at more normal hours, two outstanding technical achievement awards given for the following work reported here at PVSC42:

Design Flexibility of Ultra-High Efficiency 4-Junction Inverted Metamorphic Solar Cells

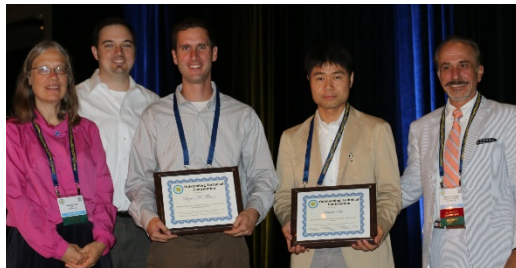
Ryan M. France¹, John F. Geisz¹, Ivan Garcia^{1,2}, Myles A. Steiner¹, William E. McMahon¹, Daniel J. Friedman¹, Tom E. Moriarty¹, Carl Osterwald¹, J. Scott Ward¹, Anna Duda¹, Michelle Young¹, Waldo Olavarria¹

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High-Efficiency Thin-Film Silicon Solar Cells on Honeycomb Textures

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Congratulations to both teams on such outstanding work.

Following this it was on to plenary talk in Areas 1, 7, and 8.

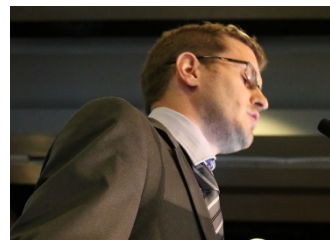
In **Area 1**, Albert Polman of FOM Institute AMOLF presented excellent results using nano-imprint lithography to create metallic nanophotonic structures for light trapping and manipulation. Light trapping structures and results were shown across an array of technologies including Si, thin Si, CIGS and GaAs. The results are very encouraging for including photonics approaches to replace ITOs in thin organic and inorganic PV cells.



In **Area 7**, Brian Spence of Deployable Space Systems spoke about new flexible blanket solar arrays that are rapidly gaining market interest. This is due to their high potential for increased performance and lower costs. These benefits are particularly important as electric thrusters replace chemical motors, critically saving 50% of spacecraft mass.



In **Area 8**, Laurent Lombez of UMR CNRS EDF Chimie Paris Tech described hyper spectral imaging PV devices. He showed how luminescence can be analyzed quantitatively to provide spatial mapping of the current and voltage performance of all types of PV devices. The technique is non-destructive, can be performed on complete junctions, and can provide a detailed understanding of the mechanisms that limit the device. The technique can even provide information on third-generation PV devices such as hot-carrier studies, and intermediate band concepts.



After morning tea break more oral sessions got under way.

In **Area 1**, Light Management, A lively session with highlights including Stephane Collin (LPN-CNRS): Engineering of critical coupling in an array of resonant metallic nanoscatterers on a thin-film semiconductor slab. Light is absorbed over a broad spectral range with an efficiency beyond the $4n^2$ limit. Sunita Darbe (Caltech): Dielectric gratings composed of resonant Mie scatterers show well-defined spectral reflection bands. This type of optics can serve as an efficient spectrum splitter in multijunction solar cell architectures. Lourens van Dijk (Delft): Showed the use of simple 3D printing to create low concentration optical concentrators. This effect leads to optical trapping and improvement in cell EQE. Shelby Vorndran (Univ. Arizona): Experimental results were shown on spectrum splitting using Gerchberg-Saxton algorithm. Method shows possibility to achieve flat, compact spectrum splitting. Ken Wang (Stanford): Showed how to achieve perfect antireflection coatings based on optical resonances.

In **Area 2**, Progress in CIGS, highlights included an Impressive presentation for ZSW with record efficiency of 21.7%. Improvements in both blue and red regions are a result of treatment after CIGS deposition. This treatment enables a lower band gap minimum in the grading and a thinner CdS layer.- Best student award finalist B. West of Arizona State applied x-ray beam induced current and x-ray fluorescence on the nanoscale to correlate CIGS layer composition and collection from grain core and grain boundary regions.- L. Mansfield of NREL reported the properties of Sb doped CIGS. Photoluminescence measurements provided detailed insights into the defect properties.- M. Edoff of Angstrom Solar Center, Uppsala demonstrated a novel gas flow sputtering configuration for CIGS films. By adding Se in a hybrid process during sputtering, an efficiency of 13.7% was obtained. - Realization of flexible CIGS solar cells on polyimide foils with high efficiencies was reported by D. Greiner of Helmholtz-Zentrum Berlin. The growth process was understood using an impressive in situ, real time energy dispersive x-ray diffraction capability.

In **Area 3**, Wafer bonding, transfer printing, Frank Dimroth demonstrated a four junction bonded III-V cell with 46.1% efficiency at 312 suns based on an engineered InP/GaAs substrate, and described the use of the bonding technique to provide several paths to higher efficiency structures. Myles Steiner

demonstrated voltage enhancement in the upper junction of a mechanically stacked four-junction III-V cell by the implementation of a low-index selective reflector between the junctions, with a four-terminal efficiency of 38.8% at one sun. Mark Goosky demonstrated GaAs/InP bonds that achieved equivalent bond resistance to InP/InP bonds. Matthew Lumb presented 2-J and 3-J component cells for future mechanically stacked 2J-2J and 3J-2J structures bonded with AsSe₃ material. Two terminal, four terminal, and voltage matched multiterminal devices were outlined for a product roadmap, and a 44.7% transfer-printed 4J cell was demonstrated.

In **Area 4**, Passivated Contacts, Upadhyaya from Georgia Tech presented 20.9% large area n-type silicon solar cells incorporating a rear passivated contact made by creating a tunneling silicon oxide plus LPCVD of a doped silicon layer. Moldovan from Fraunhofer ISE presented different ways of growing a tunneling oxide, comparing planar and textured surfaces. Tomasi from EPFL gave a very clear presentation on the low injection tail in lifetime suggesting an optimization of a-Si/TCO thicknesses for silicon heterojunction structures. Koswatta from ASU presented fundamental simulations of selective contacts. Yang from ANU presented 20.5% n-type Si solar cells with SiO₂/TiO₂ selective contact. Stradins from NREL presented iVoc and SunsVoc results on initial work toward a passivated contact, ion implanted, IBC structure.

In **Area 7**, Blankets, Space Experience and Mobile Power, Mark O'Neil presented new geometries for Fresnel, low concentration ratio (~4-6X) lenses with a tracking photovoltaic receiver, reducing the spacecraft tracking requirements. Vanguard Space Technologies presented progress on automated cell lay down and encapsulation for solar blankets. MicroLink Devices reported on cell and array development of flexible, epitaxial-lift-off, III-V multi-junction cells, for high specific power applications for space and UAV applications. Sharp Corp. and JAXA presented on the "space solar sheet" blanket technology, with separately optimized IMM cells for high and lower radiation environments. AFRL presented results from MISSE-8 solar cell experiment featuring IMM three and four junction cells as well as semiconductor bonded cells and quantum dot doped GaAs cells. NASA Glenn presented on the current deep space solar powered mission to Juno, a moon of Jupiter and the plans for solar powered "Europa Clipper" mission to the Saturn moon.

In **Area 11**, Field reliability, experience and soiling, Kazmerski et al presented a fundamental study using AFM to directly measure the forces required to dislodge various dust particles from glass and low surface-energy surfaces. These can range from far less than 40nN for treated surfaces to more than 280nN for organic particles with humidity on glass surfaces. Best Student Paper Finalist Arash Sayyah demonstrated an electrodynamic screen to remove dust from glass surfaces exploiting dielectrophoretic forces from AC waveforms applied at microelectrodes spaced on a surface. Average I_{sc} restoration of about 95% was achieved; higher voltages are needed in humid environments. Werner Herman presented a 1.5-year study of soiling effects on standard, AR, and textured glass in Tempe and Chennai, showing 3.7% and 2.3% losses for standard glass, respectively. Deeply-textured glass shows significantly larger soiling and slightly less self-cleaning recovery. In general effects are largest at high AOI. Non-uniformity of soiling is a major contributor to loss. John Wohlgemuth presented a rogues' gallery of failure modes from a variety of older (90's-era, largely) PV sites. De-laminations were found to be one of the most

common modes, yet detecting this in reliability testing still remains a challenge.

In the **Joint Areas 8 & 9**, Testing methods and quantification, Markus Mundus announced and described a first-of-its-kind apparatus to directly measure the external quantum efficiency (EQE) for a CPV module- Sarah Kurtz presented a technique to analyze EL images of modules to quantify the change in module power as a function of the degree of cell cracking. The technique could lead to a metric to support acceptance testing for installed modules.

During the lunch break where attendees got to sample some of the local food-truck fare (the Percival brisket was very good!), another poster session got under way with Areas 1, 2, 3, 4, 8, 9, 11. Once again there was high interest levels with many posters surrounded three people deep. The following posters received awards in their respective areas:

Poster Award Winners

Area 1: Theoretical Efficiency Limits of a 2 Terminal Dual Junction Step Cell, S Abdul Hadi et al, Paper 376

Area 2: Cu Profiles in CdTe Solar Cells, A Moore, T Fang, J Sites, Paper 411

Area 3: Modeling of Gas Curtains in a Dual Chamber Hydride Vapor Phase Epitaxial Photovoltaic Growth Reactor, K Schulte et al., Paper 427

Area 4: Double-Heterojunction Crystalline Silicon Solar Cell with Electron-Selective TiO₂ Cathode Contact Fabricated at 100 C with Open-Circuit Voltage of 640 mV, J Jhaveri et al., Paper 454

Area 8: Local Photocarrier Dynamics in CdTe Solar Cells Under Optical and Electron Beam, Heayoung P. Yoon et al., Paper 496

Area 9: Understanding Next Generation Cadmium Telluride Photovoltaic Performance due to Spectrum, M Lee et al., Paper 514

Area 11: Performance and Reliability of PV Inverter Component and Systems due to Advanced Inverter Functionality, J Flicker, J Neely, S Gonzalez, Paper 542

In the afternoon oral sessions were the following highlights:

Area 1 – Quantum Dot and Intermediate Band Solar Cells. Seth Hubbard showed InAs QDs with unique AlAsSb cladding layers for more favorable alignment for IBSC, giving an extension of EQE out to 1800nm. Tian Li showed results of evidence of two photon non-linear dependence of photocurrent on intensity in the InAs/GaAs QD system. Shigeo Asahi showed two step photocurrent generation using the DWELL structure of AlGaAs p-i-n architecture for an IBSC approach. Terry Yang showed interesting results investigating the middle junction of a proposed Si-based triple junction device. Alternating layers of Si-rich oxide and SiO₂ to promote growth of dope Si nanocrystals for sub-bandgap energy conversion. Taizo Tanibuchi from Kobe University showed a very unique Time of Flight experiment revealing interesting carrier dynamics of confined QDs in an electric field. Yushuai Dai of the Rochester Institute of Technology performed interesting carrier loss probability calculations using

governing carrier generation and recombination rate equations to explain her sub-bandgap conversion EQE data.

Area 2 – Worldwide Industry Advances. A very interesting presentation by Dr. Nakamura of Solar Frontier showing that composition fluctuations among grains reduces their champion 20.9% cell's Voc of 686 mV by an estimated 30mV below its full potential. Dr. Kratzert's presentation from Solibro quantified impacts in manufacturing of time delays between certain process steps and identified cleaning steps for modules-in-process which can protect from performance losses. Dr. Kimball from Miasole applied in line metrology and circuit modeling to estimate the effect of gridding process variability on cell performance. He found that distributed element circuit modeling is a powerful tool in this capability. Electroluminescence was an effective tool for the metrology. Dr. Stegemann reported the application of nanosecond laser pulses for generating the heat needed for the P2 interconnection in CIGS modules after TCO deposition and simultaneous with P3 scribing. The heat affected range was found to be small enough such that the approach outperformed mechanical scribing. Dr. Horowitz reported NREL's development of a detailed bottom-up CIGS manufacturing cost model and concluded that it is competitive with c-Si manufacturing in the US.

Area 3 – Lower Cost III-V Solar Cells. This session was dealing with the interest of lowering the cost of high efficiency III-V solar cells to the level where they can be used for flat plate photovoltaic applications. Invar Aberg presented an extended oral presentation on nanowire solar cells. InP nanowire arrays were used in the past. To lower the cost, now GaAs nanowire solar cells were investigated and reached 905 mV and efficiencies up to 15.3 % as independently confirmed by the Fraunhofer CalLab. This new record value was achieved using only 13 % of the surface area. In the future such devices may be produced by Aerotaxy. Sung-Min Lee from the University of Southern California printed arrays of very thin (200 nm active layer) GaAs solar cells and showed promising performance up to 16 %. Kenneth Schmieder from NRL presented data for fast growth of GaAs cells with 56 micrometer per hour and found that additional defects are introduced due to the high growth rate. This could be related to the EL2 defect (As anti-site) by DLTS and the defect density was found to increase from below 10^{14} cm^{-3} at 14 microns/h growth rate to above 10^{15} cm^{-3} at 56 microns/h. Elisabeth McClure from Rochester Institute of Technology investigated growth on poly GaAs and Ge with grain size of 6-0.15 mm. Devices grown on poly-Ge had almost no degradation in Jsc but had lower Voc of 0.89 V. Efficiencies of 11.9% obtained with no ARC.

John Simon from NREL discussed the use of hydride vapor phase epitaxy for low cost growth of GaAs. HVPE allows very high growth rates at low V/III ratios and lower material costs compared to MOVPE. A self-built reactor was designed with two chambers which allowed reaching high quality interfaces. GaAs solar cells were grown in this reactor at 1.8 microns/min reaching solar cells with 960 mV without front passivation and efficiencies of 16.5 %. Also first promising results of GaAs solar cells with GaInP passivation were shown.

Area 4 - Device Physics and Analysis. Paula Bronsveld (ECN) described how the IBC-HIT is the "Wollmilchsau" of c-Si PV if it can be manufactured inexpensively, as is being pursued at ECN. In her studies, in-situ masking led to lower recombination than patterned etching, although it was still limited by poor Ag paste adhesion. Andreas Fell (ANU) showed that for c-Si solar cell modelling, generation

profiles can be well represented by a simplistic optical model containing just four parameters: front-surface transmission and three constants representing the effective number of light passes.

Area 7 – Space Arrays and Structures. Inspiring presentation on the need of high-voltage, high-powered solar array technologies (up to 300kW and possibly higher!) for solar electric propulsion which will enable many new and ambitious NASA deep-space missions.⁵⁷³: Due the technological advances in high-powered solar array structures for future missions, this presentation provided insights of key design metrics where novel design concepts can be traded using these metrics.⁵⁷⁴:This talk presented technology status of the UltraFlex and MegaFlex arrays, one of the leading flexible blanket solar array designs generating high mass and packaging performance for spacecraft.⁵⁷⁵:A new solar array concept was presented that takes advantage of high strain composite materials to achieve low mass and compact packaging. Clever design concept that couples deployable structure to PV area.⁵⁷⁶: A novel deployable solar array was presented that leverages low-cost PV and solar sail structures into a cone-shaped array that is insensitive to solar pointing precision. This array is targeting nano-satellite sizes and power levels around 100 W.⁵⁷⁷: Water-cooled solar array panels are being designed for the Solar Probe Plus space mission. These unique panels require new testing methodologies to measure space environment survivability.

Area 9 – System Performance Modeling. Nils Reich presented a combined technique of grouping power plants and using an adjusted period to reduce risk investment risk. Ken Sauer showed improvement to guarantee results by tuning model parameters to better represent as-built performance. Alexander Phinikarides showed 7 years of monitored degradation data using the Arima method. Katherine Klise described asymmetrical air mass modifiers for morning vs. afternoon at three sites in the United States. Sara MacAlpine introduced a shade impact database that results in a large improvement in SAM, but is also available for public use.

Joint Area 2, 8 – Characterization of CdTe PV. Bulk Lifetime, Doping and Recombination in CdTe:P Single Crystals, James Burst from NREL reported on efforts to improve CdTe material quality to 'GaAs quality' in terms of combined higher doping and long minority carrier lifetime. Using Cd-rich CdTe single crystals they demonstrated near radiative-limited lifetime with phosphorus doping up to 1×10^{17} and lifetime up to 400 ns. Using these methods they also demonstrated a single crystal CdTe device with Voc of 1017 mV. T. Paulauskas of UIC presented a unique study of fabricated bi-crystal grain boundaries at different mis-orientation angles. They reported high resolution TEM images of atomic positions at different grain boundaries, as well as 2PE-TRPL lifetime images in the vicinity of these GB's. Atomistic simulations of grain boundaries in CdTe presented by Fatih Sen of Argonne National Lab used atomistic simulations to calculate energies of fabricated bi-crystal grain boundaries studied. John Moseley of NREL presented spectral CL characterization of bevel-cut CdTe solar cells for different processing conditions with as deposited, Cl-treated, CdCl₂- Cu-treated, and Cu-treated cells.

In the late afternoon it was time for a poster session with Areas 1, 2, 4, 7, 8, and 9. A great session rounded out the day with a lot of discussions about the work presented with discussion continuing into the NOLA night. The following posters received awards in their respective areas:

Poster Award Winners

Area 1: Cross-sectional electric field distributions in BaSi₂ homo and BaSi₂/Si hetero pn junctions, M Baba et al. Paper 591

Area 2: The Effect of Back Contact and Rapid Thermal Processing Conditions on Flexible CdTe Device Performance, H Mahabaduge et al., Paper 630

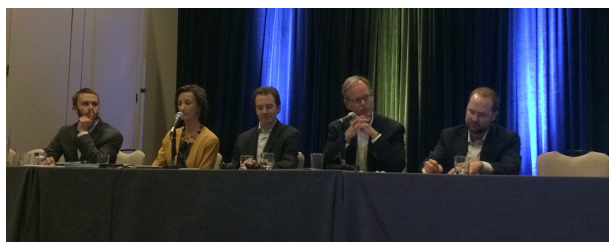
Area 4: Analysis of Copper Penetration in Selective-Emitter Silicon Solar Cells using Laser Ablation Inductively-Coupled Plasma Mass Spectrometry, J Colwell, A Lennon, Paper 649

Area 7: Carbon Nanotube Metal Matrix Composites for Solar Cell Electrodes, N Cox, J Rossi, B Landi, Paper 665.

Area 8: Temperature-Dependent Light-Stabilized States in Thin-Film PV Modules, M Deceglie et al., Paper 679

Area 9: Cost, Performance and Yield Comparison of eight different Micro-Inverters, S Krauter, J Bendfeld, Paper 715

In parallel to the poster session, the Deployment and Resiliency Panel met for a lively panel discussion with participants from the energy generation sector, energy policy, photovoltaic installation, and educational outreach for sustainable housing. The panel investigated policies and practices with respect to resiliency and in particular the role of PV in establishing an energy grid that is resilient to external forces such as natural disasters and cultural and environmental changes. The panel answered questions: Recupering from Katrina: 12 GW prior to Katrina, only now, 10 years later, regained, due in large part to installation of roof top solar lead by strong Gov't incentives. Now have among the highest PV installation in the country per capita. The devastation of the New Orleans energy grid provided an opportunity to build the city back better, which was a positive result and it highlights the fact that resiliency is typically spoken of in the rear view mirror. The extent of the devastation from Katrina and more recent events like Sandy has created a much longer social memory for the effects of natural disasters where in the past such events were forgotten within about 2 years. While the solar installation post-Katrina is a positive, without battery back-up, the system is not resilient since your home system will go down if the grid goes down. A barrier there is the immaturity and present cost of storage technology. Entergy is considering test cases, for example they are using a 7 acre field for a solar and battery field. And, given the large storage requirements, it may be more likely a utility role more than for individual homes. Adopted resiliency methods typically requires money, and if installation of resiliency technology requires private entities to increase cost there is resistance. For this, public policy must be crafted to address this.



Education was acknowledged as a challenging task. Alteration of our energy generation process is a major thing, and a homeowner needs to do research to be sure they fully understand their decisions. Many times

the public does not do the required research, or when they do, they rely on online sources that are not necessarily reliable. In response, the State and the utility like Entergy is publicizing information as much as they can. Such programs as the University of Louisiana based "Solar Power for Your Home" (www.lsuagcenter.com/solarpub). Also, a focus on elementary school education has been initiated e.g. all schools in Orleans Parish are required to be LEED certified. Community solar: Entergy has been studying this for about a year and half. Other places around the country are starting to adopt this. Entergy sees this as a financial issue - within the community, who will pay for what portion and how much. PV is not a replacement for efficiency, these must be done hand in hand. Net-metering remains a contentious issue.

That rounds out the highlights for Wednesday, there will be many more to come in the days ahead!

IEEE ELECTRON DEVICES SOCIETY - MEMBERSHIP PROMOTIONS FOR 42nd PVSC ATTENDEES

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