Wednesday Highlights

Wednesday at the 43rd PVSC had an early start for some, with the traditional Sun Run kicking the day off, before more technical sessions. The Morning plenary session consisted of excellent presentations in Areas 5, 7, and 10.

In Area 5, Thorsten Trupke from the University of New South Wales, started the day with an excellent plenary talk on the latest developments in photoluminescence characterization in photovoltaics. He showed how line scanning for brick inspection is becoming a powerful method in which artefacts are greatly reduced. He then presented new results on obtaining a spectral response type data from photoluminescence measurements. He finally showed how line scanning now also allows use of PL imaging on full modules for quality control, as an alternative to the more conventionally used EL imaging.

For Area 7, Greg Carr from the Jet Propulsion Lab presented the current trends in power systems for deep space missions. Combining the latest advances in space PV with tailored mission designs, in particular with regard to the thermal subsystem, PV powered space missions to Jupiter and even Saturn are enabled, which previously were possible only with the help of radioisotope power sources. An important contributing factor is the accurate characterization of the cell performance in low light intensity, low temperature space environments.

Area 10 saw Greg Ball cover the important problem of firefighter response to fires with PV arrays present. The potential for poor public perception of PV based on these incidents was stressed. Some key operational approaches were outlined as well as structural features that can be used to help make firefighters jobs easier and safer when arriving at the scene. The need for proper training and for improved risk mitigation strategies, such as multiple level ground and string disconnects was highlighted. Detailed feedback from firefighters was sought to help inform these approaches, with improvements ongoing.
In the morning oral session, there were presentations in Areas 1, 2, 5, 7, 8, and 10, with the following highlights sent by the Session Chairs:

**Area 1 - Light Management for Quantum Confined Photovoltaics**

*Ken Watanabe* demonstrated an optical path length enhancement of 4.8 times by including a randomized texture on the back surface of a MQW solar cell, resulting in an increase in current of 1.5 mA/cm², and a factor of three improvement in radiative efficiency. *L. Zhu* presented results from the addition of a DBR to a MQW solar cell, which indicated internal radiative efficiency of 50%, which is a significant improvement over non-MQW devices. *C. Hong* showed enhanced radiative properties under concentration (200x) as compared to bulk by using MQW with DBR structure on the back and selective filter at the front to suppress the out-coupling of the spontaneous emission (Voc DBR: 8mV/DBR SF@910nm: 11.5 mV). *Brittany Smith* (pictured) was able to integrate various back reflector designs in a QD solar cell, with a flat back reflector showing a doubling of the sub-bandgap current collection from the QDs. Additionally the use of a rear junction design was able to show an improvement in Voc of 40 mV over a conventional structure. *Frederica Cappelluti* presented modelling results that showed predicted voltage recovery by doping QDs, which reduce radiative and non-radiative recombination within the QDs. Additionally an improved QD QE and a 1.4% absolute efficiency increase with 18 electrons/QD were predicted via simulation over a control structure.

**Area 2 - Worldwide Industry Advances: Pushing Efficiency Limits**

*Rui Kamada* discussed how Solar Frontier developed their CIGS solar cell technology up to 22.3% efficiency. After a 1st phase on improvement of the current using a ZnO:B window layer, they focused on Voc improvement. After analysis, they focused on surface passivation (by KF PDT) and buffer layer optimization (using (Zn,Mg)O). *Dr. Gloeckler* discussed the recent progress at First Solar and their
22.1% record cell and 18.6% module efficiency. Excellent progress in current has been made, with improvements at both the low and the high wavelengths. Lifetime was enhanced with values up to 100 ns. The 3 phases of progress were on the back contact (ZnTe:Cu), the lifetime and finally the grading of the absorber layer (CdSexTe1-x). Dr. Lundberg presented the recent progress at Solibro on their CIGS modules and cells, by introducing KF PDT. Voc is improved by the treatment but FF is reduced, while the current can be improved thanks to a thinning of the CdS. By GDOES analysis, they show a reduction of the Cu and Ga at the surface, inducing a formation of a K-In-Se compound at the surface. This leads to a 17.2% champion module. Loss differences between cells and modules were also discussed and solutions proposed, notably addition of metal grids.

**Area 5 - Characterization of c-Si and mc-Si**

Theresa Strauch presented a method for measuring and classifying grain structure in different types of multicrystalline silicon wafer across various ingots. Amanda Youssef presented temperature and injection dependent Photoluminescence imaging data to obtain spatially resolved defect parameters on oxygen related defects in Cz wafers. Johnson Wong presented the capabilities of two dimensional device simulation using Griddler to simulate, understand and quantify loss mechanisms in silicon solar cells. G. Koutsourakis presented a novel method to characterize solar cells based on compressed sensing current mapping methods. P. Sonntag discussed the use of LBIC to map diffusion lengths on Si solar cells, where simulations and experiments were combined to de-convolute bulk from interface effects. K. Bittkau reviewed the use of NSOM methods to map light-matter interactions in Si solar cells, including light trapping.

**Area 7 - Space Array Technologies**

Andrew Gerger of SolAero provided an update on Solar Probe Plus progress, including completion of exposure testing to extreme high solar intensity environments, pre-conditioning protocol, LED vs broadband comparison and start of flight strings. Ben Cho of Solaero presented the latest status of the IMM cell manufacturing improvements as part of the AFRL Mantech program, with the objective of scaleup to a production scale product at affordable cost (MSL7). Don Walker of Aerospace Corp presented on the Picosat/Aerocube program overview and history, and nano-sats were discussed in particular, with improvements in attitude control, including Aerocube 8. A stable testbed for solar cell testing has been developed, and is continually being refined.
Area 8 - PV Performance Modeling (I)

The session included three different presentations on performance modeling of PV modules with the influence of spectrum changes due to Air Mass, AOD and Precipitable water. I. Geisemeyer (Fraunhofer ISE) presented measurement results of Angle Of Incidence characterization of the spectral response for different texturized surfaces.

Area 10 - Advanced PV Inverters - Enabling Further PV Integration

Fei Ding presented the results of a study involving quasi-static time-series distribution system analysis of a SDGE (San Diego Gas and Electric) circuit to investigate the voltage related impacts of operating PV inverters at various fixed power factors and volt/VAR curves. Jay Johnson discussed, with the advent of a wide array of advanced PV inverter functions, a study designed to determine the desirable frequency-watt PV inverter control in order to provide frequency regulation/reserves for the overall electricity grid. The settings of frequency-watt functionality were optimized to minimize overall total cost of implementation (considering blackout, curtailment and frequency regulation costs). Farid Katiraei presented work completed, in collaboration with SDGE, in the power-hardware-in-loop (PHIL) testing space. Specifically, PHIL derived P-Q characteristics, fault ride-through tests and droop characteristics were presented as good examples of how utilities can validate PV inverter capability/operation. John Seuss described a study he completed investigating the use of advanced PV inverter controls to enable the widespread use of PV while operating PV curtailment in an optimal way. Using volt/watt control, the specific parameters of such a control was optimized for dispatch windows of 1 and 5 minutes. Matt Rylander presented a paper describing methods that utilities could use for choosing the specific settings for advanced PV inverter settings without the necessity of performing detailed PV inter-connection studies. Different approaches, varying in the amount of information needed to determine settings versus how much the approaches increase the PV hosting capacity of a circuit, were investigated. Results showed that all proposed methods can increase PV hosting capacity and that methods that require more information regarding the distribution system being interconnected result in incrementally increased hosting capacity. Soenke Rogalla discussed a power quality issue of PV inverters, namely harmonics. Rogalla described how the harmonics seen at a PV system are the sum of source-driven and resonance-driven harmonics. Analysis of data from a large PV plant, experiencing voltage-related power quality problems, resulted in the determination that resonance-driven harmonics were the cause.
It was then time for both the PV Jobs Fair and the lunchtime poster session, where boxed lunches were available for people to sate their hunger while perusing the presentations on offer in Areas 1, 2, 3, 6, 9, and 11. The winners of the poster awards in each Area were:

**Area 2 - Contacts, Buffers, Substrates and Interfaces**
Monocrystalline CdTe/MgCdTe double-heterostructure solar cells with a passivated ZnTe hole-contact layer, Jacob J. Becker$^{1,2}$, Calli M. Campbell$^{1,3}$, Yuan Zhao$^{1,2}$, Mathieu Boccard$^2$, Ernesto Suarez$^{1,2}$, Maxwell Lassise$^{1,2}$, Yong-Hang Zhang$^{1,2}$, $^1$Center for Photonics Innovation, $^2$School of Electrical, Computer and Energy Engineering, $^3$School for Engineering of Matter, Transport and Energy, Arizona State University, Tempe, AZ, United States

**Area 5 - Characterization 1**
Spatially Resolved Characterization of ARC Films on Multicrystalline Silicon with Non-contact Surface Voltage Technique, Alexandre Savtchouk, Piotr Edelman, Marshall Wilson, Andrew Findlay, Jacek Lagowski, Semilab SDI, Tampa, FL, United States

**Area 6 - Characterization of Organic and Perovskite PV**
Thin-Film Flexible Barriers for PV Applications and OLED Lighting, Ahmed Salem$^1$, Hylke Akkerman$^1$, Wiel Manders$^1$, Wilhelm A. Groen$^1$, Paul Poold$^1$, Merve Anderson$^2$, $^1$Holst Centre (TNO), Eindhoven, Netherlands, $^2$Heliatek GmbH, Dresden, Germany

**Area 9 - Field Experience, Soiling, and System Reliability**
Correlation of Electrical and Visual Degradation Seen in Field Survey in India, Rajiv Dubey$^1$, Shashwata Chattopadhyay$^1$, Vivek Kuthanazhi$^1$, Jim Joseph John$^1$, Chetan Singh Solanki$^1$, Anil Kottonharayil$^1$, Brij M Arora$^1$, K. L. Narasimhan$^1$, Juzer Vasi$^1$, Birinchi Bora$^2$, Yogesh Kumar Singh$^2$, O.S. Sastry$^2$, $^1$National Centre for Photovoltaic Research and Education, Indian Institute of Technology Bombay, Mumbai, India, $^2$National Institute for Solar Energy, Ministry of New and Renewable Energy, New Delhi, India
Area 10 - Grid Integration of PV
High Temporal Resolution Load Variability Compared to PV Variability, Matthew Lave¹, Jimmy Quiroz², Matthew J. Reno², Robert J. Broderick², ¹Sandia National Laboratories, Livermore, CA, United States, ²Sandia National Laboratories, Albuquerque, CA, United States

Joint Area Session - Joint Session (1, 3, 4, 7): III-V PV via Alternative Substrates and Growth Methods

Development of a Kinetic Rate Law for the Optimization of GaAs Growth by Hydride Vapor Phase Epitaxy, Kevin L. Schulte, John Simon, Nikhil Jain, David L. Young, Aaron J. Ptak, National Renewable Energy Laboratory, Golden, CO, United States

Following the long lunch break there was another set of oral sessions with some of the highlights from the 2.30-4.00 pm session included below.

Joint Area Session - Joint Session (1, 3, 4, 7): III-V/Si PV

Steven Ringel of Ohio State University kicked off this session with an invited talk on the development of fully epitaxial 2- and 3-junction cells on Si, demonstrating an impressive feat of the first 3-junction device on Si via a single MOCVD growth run. Romain Cariou of Fraunhofer, ISE shared an impressive new 1-sun record for a wafer-bonded, triple-junction device on Si of 30.2% (GaInP/AlGaAs//Si). Adele Tamboli (NREL) presented joint results from NREL and CSEM on the development of mechanically stacked 4 terminal cells, with a verified record tandem efficiency of 29.8% under 1 sun. Michelle Vaisman of Yale University presented impressive MBE growth optimization to reduce threading dislocation density in GaAsP on Si, obtaining a 15.3% efficient single-junction GaAsP solar cell. We closed our session with a presentation by Laura Ding studying lifetime degradation of Si during subsequent MBE III-V growth. She presented defect parameter contour mapping as a new method for defect characterization in Si.

Area 2 - Progress in CdTe Technology

Teresa Barnes of NREL discussed the effect of dopants in CdTe and presented results on high lifetime CdTe grown by MBE. She presented results on CdTe doped with As up to \(10^{17}\) with acceptor concentration on the order of \(2\times10^{16}\). As is a better dopant than the Cu that is considered to be active in today's devices - this work could point the way to a future high efficiency structure. Tursun Ablekim spoke on point defects in CdTe, noting Cd vacancies have an important impact on conductivity control - and yet the vast literature on their study reveals ongoing controversy about their energy levels. Ablekim (Washington State Univ.) uses thermo-electric effect spectroscopy to investigate in a fundamental study
of defect energies and identities. They were able to grow off-stoichiometric CdTe and identified the activation energy for cadmium and tellurium vacancies. **Eric Colegrove** of NREL spoke about experimental studies of P and Sb diffusion in single- and poly-crystalline CdTe. Doping in CdTe is of current interest in the push to high voltage devices. They calculated activation energies for bulk and grain boundary diffusion. The longstanding question about fast and slow components of bulk diffusion was resolved by invoking atomistic mechanisms verified by the measured activation energies being confirmed by DFT. **Da Guo** of Arizona State University discussed results from a numerical solver to use experimental Cu diffusion data in CdTe to simulate its effects on device band structures. The materials model includes both diffusion and defect reaction of the Cu. The modelling predicts the realistic performance and ageing behaviour of devices. **Tao Song** Arizona State reported work on the optimum choice of emitter layer for CdTe solar cells. Optimum band schemes that suppress interface recombination, but not photocurrent were described. The results indicate that (Cd,Mg)Te and Cd(S,O) is a better choice than the traditional CdS.

**Area 4 - Contact Formation & Module Integration**

A new technique for metallization of heterojunction solar cells by drop of demand ink jet technology for the intention of saving silver was presented by **April Jeffries** from Arizona State.

**Area 5 - New types of measurements/instruments**

**Riley Brandt**, reported on using computational modelling and machine learning techniques for materials and device discovery. Impact - as computational power increases, discovery can be accelerated particularly in cases where experimental costs are high and/or time-consuming. **Ashley Morishige** spoke about using synchrotron-based micro X-ray fluorescence to create elemental maps of samples. Conventional "step-wise" scanning is slow, limiting resolution and the area that can be scanned. A new technique, "Flyscanning", utilized continuous motion to scan a sample more rapidly, enabling higher resolution (~4x) or larger areas (~7x) for the same amount of beam time.

**Joint Area Session - Joint Session (8, 9, 11): Soiling**

**M. Mazumder** presented electrodynamic film screens as a solution for removing dust without water. Challenges and progress with the current technology were presented. The A. **Sayyah** presentation followed up the work done by Mazumdar talking about a few issues with EDS: a limitation with particle size removal and sensitivity to humidity levels. **Mike Deceglie** presented an automated method to extract soiling rates using the Theil-Sen estimator. **Hassan Qasem** presented on detecting dust using image processing.
Area 10 - PV Paired with Energy Storage, Grid Economics and Bulk System Impacts

Meng Tao of ASU presented a well planned out macro analysis of this battery technology, over a very long range. Reno et al., gave detailed analysis of solar variability for Vreg changes and mitigating with distributed storage, compared to dynamic VAR control to mitigate ramp ramps. Litjens et al., reported on the use of load curves and forecast to determine value of storage. Chaomin Zhang (pictured) of ASU presented results of LCOE analysis for 5 different tariff assumptions. Magerko then showed the benefits of active grid support by having a solar reserve. Finally, Barry Mather’s work on the distributed PV impact on bulk power systems was presented, discussing how transmission events will affect voltage sags at substation level.

Finally, in the late afternoon poster session the following papers received awards:

Area 1 – Quantum Confined Materials

Growth of InAs Quantum Dots in a Metamorphic InGaAs Bottom Cell of an Inverse Metamorphic Solar Cell, Michael A. Slocum1, George Nelson1, Brittany L. Smith1, Rao Tatavarti2, Seth M. Hubbard1, 1Rochester Institute of Technology, NanoPower Research Labs, Rochester, NY, United States, 2Microlink Devices Inc., Niles, IL, United States

Area 2 – Device Characterization and Modeling

Mechanisms for Light-Soaking Induced Carrier Concentration Changes in the Absorber Layer of Cu(In,Ga)Se2 Solar Cells, Rouin Farshchi, Benjamin Hickey, Geordie Zapalac, Dmitry Poplavskyy, MiaSole Hi-Tech Corp, Santa Clara, CA, United States

Area 3 CPV Cells and Testing

A Programmable Solar Simulator for Realistic Seasonal, Diurnal, and Air-Mass Testing of Multi-Junction Concentrator Photovoltaics, Tasshi Dennis1, Chanud Yasanayake1, Tim Gerke2, Alex Payne3, Lars Eng3, Brent Fisher4, Matt Meitl4 1NIST, Boulder, CO, United States, 2Fianium, Inc., Eugene, OR, United States, 3Silicon Light Machines, Sunnyvale, CA, United States, 4Semprius, Inc., Durham, NC, United States

Area 4 – Junction Formation and Device Analysis
Effects of Injection-Level Dependent Bulk Lifetime on Cell Properties, **Henry Hieslmair**, *SunEdison, Belmont, CA, United States*

**Area 7 – Space PV Technologies**
Test Results of Radiation Resistant Coatings Integrated with Flexible Substrate Materials and Active Solar Cells, **Carol L. Martinez & Samuel F. Pellicori**, *Optical Coating Solutions, Inc., Camarillo, CA, United States*

**Area 8 – PV Module, and System Modeling**
Miniaturized test array as a means to determine the energy harvest of bifacial installations, **Hartmut Nussbaumer, Giordano Petrzilek, Markus Klenk, Steve Schartinger, Nico Keller, Thomas Baumann, Fabian Carigiet, Franz Baumgartner**, *Zurich University of Applied Science, SoE, Winterthur, Switzerland*

So, that concludes the highlights of the Wednesday of the 43rd IEEE PVSC conference!

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