



Friday of the 43rd IEEE Photovoltaic Specialists Conference provided a half-day program, with more excellent work being reported.

The following highlights were provided by Session Chairs for the morning oral sessions:

#### **Area 1 - Optical Concepts and Thin Absorbers**

**Eli Yablanovitch** discussed advantages of light trapping for cell operating voltage, increasing voltage by 0.1 V. Specifically, for a thick device expect a voltage boost of 66 mV and for an optically thin device, expect about 102 mV. **Urs Aeberhard** discussed the need for a quantum PV model for very thin cells. He described a 60 nm thick p-i-n GaAs cell and how the current is modified in this model. **Andrea Cattoni** described both the modeling and experimental results of a 200 nm GaAs solar cell with a nanostructured mirror. **S.M. Han** presented their recent work on optical absorption enhancement using symmetry breaking-structures for applications in thin silicon solar cells. The low-cost patterning technique involves rotating nanoimprint masks followed by anisotropic etch. **S. Vorndoran** demonstrated diffractive optical elements for spectrum splitting applications.

#### **Area 2 - Advances in Buffer Layers, Interface and Back Contact Engineering**

**Zhao** of ASU reported on an 18.5% total-area efficiency single-crystal CdTe device on InSb. Other double heterostructures on n-type CdTe epi-layers suggest high lifetime with carrier density of  $\sim 10^{17} \text{ cm}^{-3}$ . Also discussed was the use of a-Si passivation/contact layer on the front of the device, resulting in an open circuit voltage greater than 1.1 V. **Edoff** then reported on the use of ALD  $\text{Al}_2\text{O}_3$  passivation layer to improve 500 nm absorber CIGS devices. **Lepetit et al.** have found that the KF post deposition treatment leaves a K-In-Se compound on the CIGS surface. They deposited a  $\text{KInSe}_2$  layer as a replacement for the KF post deposition treatment. **Sevvana et al.** discussed the use of MoNa as a back contact for their flexible CIGS for controllable sodium incorporation. Finally, **Burst et al.**, discussed the challenges of how high lifetime and high carrier concentration might be incorporated into an actual polycrystalline

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## International

device and what are the concerns. Some devices constructed on crystalline p-type CdTe with low-temperature CdS were also discussed.

### Area 5 - PL/EL methods and interpretation

**Uwe Rau** shared a waterfall analysis of Voc losses for 10 PV absorber materials. **Soren Jensen** applied two-photon PL methods to studying KF-treatment of CIGS absorbers. **Thomas Unold** detailed a spectrum fit modeling approach for quantifying PL images. **John Katahara** shared a modeling approach to study PL quantum yield, accounting for high PL quantum yield related to semiconductor band tailing. **Francois Gibelli** presented a method for extracting carrier temperature and electrochemical potential based on hot carrier PL spectra. **Masahiro Yoshita** shared absolute EL results from 1J and 3J solar cells, comparing the emission rate results by several EL methods and demonstrated the ability to accurately predict sub-cell Voc.

There was one more set of oral sessions with some of the highlights listed below.

### Area 1 - Emerging Technologies

**Rebecca Saive** gave an invited talk on simulation and development of vertically triangular metal contacts which couple up to 99.9% of incoming light into the device instead of reflecting it, making them effectively transparent. She also covered plans for improving manufacturability using a process similar to nanoimprint lithography. Finally, she discussed a specific application to improving light absorption through the reduction of both grid reflection and the necessary ITO thickness in silicon heterojunction devices. **Stefan Omelchenko** discussed the effects of excitons in  $\text{Cu}_2\text{O}$ , a material with a particularly large exciton binding energy. His calculations were able to show the impact of exciton generation, which include potential improvements to current density and fill factor. **Paula Perez Rodriguez** presented on direct solar to hydrogen generation using multijunction silicon devices, with a path towards > 12% efficient triple-junction devices. **Haejun Chung** reported on modeling efforts to understand optical loss mechanisms of perovskite/silicon tandem devices. **Chung-Yu Hung** presented work on developing back-

contact thin film GaAs devices - he demonstrated that working devices can be made, and described a strategy to potentially increase future device efficiencies.

## **Area 2 - Devices & Materials Characterization and modelling**

**Jim Sites** gave a good review of CdTe and focused on the low Voc issue suggesting increased doping, better electron reflection at the back barrier, p-i-n device geometries, and removing Cu from the back contact. **Joel Duenow** focused on single crystal CdTe to show increased doping, and simultaneously achieving high carrier lifetime. **Darius Kuciauskus** showed carrier recombination around structural defects using 2 photon excitation spectroscopy and also showed local electric fields and band bending. **Michael Lloyd** investigated single crystal CZTSe reported 8.6% solar cell efficiency and the device is currently limited by bulk defects. **Pran Paul** showed the VCu-VSe defect concentration in CIGS is impacted by Na and K treatment and increased dramatically for 1-stage grown CIGS. This defect is also correlated with light induced Voc instabilities.

## **Area 5 - Nanoscale characterization**

**Paul Narchi** (Total New Energies) showed how KPFM can be used to map carrier lifetime in cross-section solar cells. **Zhibo Zhao** (MIT) discussed the implementation and limitations associated to cathodoluminescence in STEM to spatially resolve the optoelectronic properties of perovskites with nanoscale spatial resolution. **Tadas Paulauskas** (Univ. of Illinois) presented a DFT model and HR-TEM combined study to help in explaining the effect of the grain boundaries in CdTe polycrystalline solar cells. **Paul Stradins** (NREL) showed how analytical electron microscopy, e.g. EELS and EDX, can be used to determine the atomic scale effects of contact metallization on Si solar cells degradation. **Kotaro Hirose** (Tohoku Univ.) introduced super-higher-order scanning non-linear dielectric microscopy to resolve the distribution of dopants in Si solar cells. **Chun-Sheng Jiang** (NREL) reviewed how Kelvin probe microscopy can be implemented to map the surface potential of CdTe photovoltaics.

## **Joint Area Session - Joint Session (5, 8): Module and System Characterization**

**Markus Schweiger** of TUV- Rheinland looked at energy yield and module performance ratio from 5 different climate sites over 2 years, showing a variety of initial stability changes for multiple module technologies. **Chris Deline** (NREL) presented on bifacial module indoor / outdoor measurement methods and discussed the dependence of light level on the back of bifacial modules. Other presentations in the

session showed fast 10ms indoor sweeps on high capacitance modules, fast 100ms outdoor sweeps under variable conditions, and cross-tied system configurations for shade tolerance.

### **Area 12 – International Collaboration toward TW-Scale PV**

**Masafumi Yamaguchi** introduced the session by emphasizing the importance of international collaboration. Eicke Weber summarized how a workshop was held in March exploring the challenges of PV growing to TW scale. The conclusion of the workshop was that if current trends continue, we should expect PV to have deployed 3 TW by 2030. If growth rates of 20%-25% can be maintained, the deployments could reach 5-10 TW; workshop participants felt that the PV industry should be striving to reach 5-10 TW. However, current projections by many groups place PV deployments at far lower levels. Communication with the groups making the projections may better align the projections with the actual future.

Following these sessions the Closing ceremony presented an Outstanding Technical Merit Award to Ruiying Hao for her paper “Kerfless Epitaxial Mono Crystalline Si Wafers With Built-in Junction And From Reused Substrates For High Efficiency PERx Cells” (Paper # 23).

Here are the Student Award Winners:

Area	Paper #	Author	Title	Affiliation
1	353	Brittany L. Smith	Enhanced Absorption in Epitaxial Lift-Off (ELO) Quantum Dot Solar Cell by Back Surface Texturing	Rochester Institute of Technology
2	933	Yuan Zhao	Monocrystalline CdTe/MgCdTe double-heterostructure solar cells with 1.096 V Voc and 17.0% efficiency	Arizona State University
3	54	Emmett E. Perl	Measurements and modeling of III-V solar cells at high temperatures up to 400C	UC Santa Barbara
4	283	Simone Bernardini	Nano-XRF Analysis of Metal Impurities Distribution at Grain Boundaries during mc-Silicon Solar Cell Processing	Arizona State University
5	947	John K. Katahara	Voc Overestimation from Photoluminescence Quantum Yield in Disordered Absorber Layers	University of Washington
6	328	Chuanxiao Xiao	Potential Profiling Across Perovskite Solar Cells with and without SnO <sub>2</sub> as Electron-	Colorado School of Mines

			Transporting/Hole-blocking Layer	
7	903	Daniel J Chmielewski	Comparative Study of 2.05 eV AlGaInP and Metamorphic GaInP Materials and Solar Cells Grown by MBE and MOCVD	The Ohio State University
8	370	Malte R. Vogt	Increased yield of PERC compared to Al-BSF cells due to inherently lower module operating temperature	Institute for Solar Energy Research , Hamelin, Germany
9	295	Ashley E. Morishige	Lifetime Spectroscopy Investigation of Light-Induced Degradation in p-type Multicrystalline Silicon PERC	Massachusetts Institute of Technology
10	913	Jonah Crespo	Design of a Highly Efficiency Micro-Inverter	Indiana University-Purdue University Indianapolis
11	305	Kyohhei Kamono	Real Time Estimation of Areal PV Output Power Using Sunshine Duration and Power Meters	Tokyo University of Science
12	921	David Berney Needleman	Economically Sustainable Scaling of Photovoltaics to Meet Climate Targets	Massachusetts Institute of Technology

Well done to all the award winners, but also to those nominated, there were many excellent presentations, making the judges job a difficult one.

Well, that is it for the highlights of this year's conference, there has been some excellent presentations with some exciting results reported. We all look forward to next year's event where we will see the progress made and the new ideas that will be pursued.

Finally a big thank you to the following people who helped make the highlights possible, Adam Kohm for getting them online and notifying attendees, Jeremiah McNatt for helping to chase down information in quick time, John Meakin for the photography, and an extra big thank you to Sarah Kurtz for somehow finding the bandwidth to edit the draft versions sent at all sorts of odd hours. Finally, thank you to all of the session chairs for providing the session highlights, and all the presenters for providing the highlights in the first place.

The weekly highlights were provided by Stephen Bremner. Many thanks to him for doing an excellent job!