In Area 1 “Intermediate band photovoltaics” Jacob Krich gave two talks on progress in intermediate band solar cells. In the first extended oral he presented a figure of merit for intermediate band absorbers with a strong ability to predict when it is worthwhile to make devices. He showed that light trapping enables useful devices from much lower quality material. The figure of merit was shown to well describe devices using a new open source device model, Simudo, which he described in his second talk. Simudo allows treatment of the important intermediate band processes but also converges faster than Sentaurus for standard semiconductor devices. It is available at github.com/simudo/simudo

Yangyi Yao presented an InAs/GaAs quantum dot realization of IB PV. It was found that the photon saturation density was not high enough even at 170K to improve the efficiency of a solar cell using an intermediate band architecture. Luc Robichaud explained how InGaN quantum dots can be used for intermediate band applications. The material study was complemented by electronic structure calculations. It was found that a maximum efficiency of 39% could be achieved in an InGaN/GaN intermediate band system, even though the band-gap of GaN is larger-than-optimal (3.5 eV) for the bulk material in an intermediate band solar cell.

For Area 1 - Novel Concepts in Fabrication, Daisy Xia gave a very interesting talk on laser power conversion at 1310 nm. She developed a detailed balance model for InAlGaAs photonic power converters that incorporated luminescent coupling. Her model predicted that a 20
junction photonic power converters would achieve 13.7V with high internal radiative efficiency and a power conversion efficiency of 60%.

Scott McClary gave an excellent talk that provided detailed materials and device properties in a new absorber material (Cu3AsS4). Polycrystalline films were fabricated and characterized using THz pump probe showing minority carrier lifetimes in the ns range. Cyclical voltammetry was used to determine limitations imposed by the buffer layer motivating the use of an alternate layer.

In Area 2 “CIGSe Modeling and Characterization” Dr. Giovanna Sozzi demonstrated the optimal Zn/Mg ratio for high efficiency solar cells using Zn(O,S) and (Zn,Cd)S buffer layers. Dr. Tara Nietzeld observed the possible formation of Cu-Se and Ag-Se secondary phases for (Ag,Cu)InSe2 when is annealed under the presence of K3. Dr. Johannes Hepp showed the use of electroluminescence and IR imaging techniques to generate a transfer function of Voc based on GGI profiles and macroscopic defects in the PV modules.

In Area 2 “Interface and Surface Modification Across Material Technologies” X. Cui presented the successful use of very thin aluminum oxide oxide layer on the surface of CZTS to enhance efficiency, especially the voltage; enhancement also seen in spectral and time-resolved photoluminescence. S. Giraldo showed how a back-surface field is created with a sputter-deposited layer of CuGa with minimal void formation. The higher efficiency results from the reduction in interfacial recombination. Most likely a layer of GaSe is formed. R. Greenhalgh made a comparison between cadmium bromide passivation and the traditional cadmium chloride. The Br does passivate the grain boundaries, but it also interacts with the MgZnO buffer layer used. Net result is a lower efficiency improvement than with the Cl process. C. Reich showed that wide bandgap materials are important in tandem solar cell application. Capping (barrier) layers are used during CdCl2 treatment of CdZnTe, CdMgTe, thus preventing element loss of Zn and Mg. Specifically CdS for CdMgTe and MgZnO for CdZnTe was shown to work.
Y. Samoilenko presented combinatorial libraries for multiple compositions for MZO. It is built by reactive co-sputtering Zn and Mg targets in one substrate. Identified optimal band gap of MZO 3.45-3.5 eV, efficiency is approaching 16%. A promising 17.4% is obtained for CdSeTe absorber. H. Sun showed that absorber and buffer interface can be passivated by ultrathin SnO2 prepared by AILAR followed by Air annealing. Improvement of Voc and FF, as well as lifetime. SnO2 optimize band alignment at interface. Grain boundaries passivation is observed by KPFM.

In Area 3 “Hybrid Tandems - Components & Modelling” the session provided a counterpoint to Tuesday’s Battle Royale session. Michael Rienaecker presented an interesting analysis of how three terminal silicon bottom cells work for tandems that are current mismatched in various configurations. He also introduced a novel hybrid PERC-POLO bottom cell to enable low cost, simple fabrication of such bottom cells. Paul Stradins discussed a circuit modeling based approach to understand three terminal tandems, providing evidence that high efficiency can be achieved regardless of top cell band gap. Jose Ripalda demonstrated a nice model for taking into account spectral variations in multijunction energy yield, as well as proposing some proposed approaches for high energy yield tandems that use less III-V material and collect diffuse light effectively. K. Kishibe presented a hydrogel-mediated bonding technology that can be used to bond substrates with micron-scale surface roughness. Excellent optical mechanical transparency, mechanical strength and good conductivity were obtained using PAM as bonding material. M. Arulanandam discussed the opportunity for a II-VI/silicon tandem, showing that silicon has no lifetime degradation after CdTe growth but the CdCl2 treatment will degrade the lifetime of the silicon device.
In Area 3 “CPV Modules & Systems” Steve Askins presented a CPV module with planar micro tracking that achieved 29% efficiency at CSTC and up to 25% energy boost with the diffuse contribution. He emphasized that planar tracking and diffuse capture are two very compatible attributes since diffuse capture can pick up power when sun moves beyond tracking acceptance angle. The module uses 42% upright metamorphic cells operating at 200X concentration and fabricated by Insolight in Switzerland. Matt Lumb presented a 5J CPV cell that achieved 35.4% that was assembled into a module using transfer printing, then placed under a compression-moulded glass hexagonal lens let array that achieved 70x concentration. Kelsey Horowitz presented a cost analysis of high efficiency solar modules for residential rooftop installation. She argued that the area restrictions on rooftops drives PV efficiency in order to reducing installation cost and LCOE. Several Micro-CPV approaches were presented. 69% of rooftops are area constrained which provides a market for micro-CPV.

In Area 4 “Devices Built with Carrier Selective Contacts” C. Allebé showed how short-annealing along with integration of (p)SiC/iOx in n-type solar cells gave a 21.7% cell efficiency, long-annealing along with integration of (n)SiC/iOx in n-type solar cells gave a 22.5% cell efficiency, the (n)SiCx contacts used industrial size cells and screen-printed metallization. Felix Hasse demonstrated an hybrid IBC structure using n-poly over tunnel oxide for n-contact and local Al-BSF for p-contact and have reached 21.8% on p-type (Ga-doped) on 2x2 cells with screen-printed electrodes. Matt Hartenstein demonstrated an innovative way of patterning the rear-side poly-Si/SiO2 IBC cells. The patterning is made by the PECVD deposition of doped oxide through ceramic masks. The shunt issue caused by dopant cross-contamination can be mitigated by capping back-side with the sacrificial undoped poly-Si or with the short RIE. Abhijit Kale presented comprehensive and convincing analysis of the tunnel layer formed by TOPCon and POLO approaches respectively. He show increase in recombination at the textured surface is caused by microroughness at the pyramid facets and nonuniformity of the oxides. The issue can be mitigated by an extra acid treatment. David Young implemented a TOPCon structure with front-side poly-Si only underneath the front metal grids by RIE etching the front poly-Si using the front metal as a mask. Jsc did not increase as much as expected due to non-uniform etching of poly-Si. Boajie Yan showed surprising result that hydrogenation of the poly-Si can be achieved in H2O ambient at 500C and showed increased H concentration at the SiO2 interface compared to other methods. The cell efficiency of 22.5% was achieved.

Area 4 - Carrier Selective Materials Optimization: E. Bruhat showed that capped AZO can withstand firing anneals up to 900C without loosing electrical properties or the underlying poly-Si contact passivation. H. Nguyen demonstrated, in a crystallized poly-Si, PL signatures from both poly-Si and a-Si:H, their relative intensities changing upon hydrogenation, anneal, and repeated hydrogenation. A. Onno presented a generalized model for contact resistivities in a solar cell, based on quasi Fermi levels and partial conductivities of electrons and holes, as well as partial drops of QFL as the carriers approach the metal electrode through a semiconducting contact. V. Titova demonstrated 20% efficient cell with back contact made of TiOx/Al layer stack, and that 350C post anneal is required to enable good passivation and low contact resistivity. T. Zhang presented an ALD supercycle process with in-situ spectroscopic ellipsometry to deposit ZnxNixO and AlxNiyO oxides as p-type passivated contact material.

In Area 4 “Advancements in Silicon Heterojunction Solar Cells” Z. Holman gave his presentation as the IEEE Stuart R. Wenham Young Professional Award winner. He gave some cost analyses on what would make an effective tandem cell, establishing target areal costs of the order tens of dollars per square metre in additional cost for the tandem cell. He proceeded to consider some examples such as III-V on silicon, perovskite on silicon and spectrum splitting configurations. M. Boccard reported on over 23.8% heterojunction solar cells with novel transparent electrodes and good surface passivation. A. Fioretti showed how lower deposition temperature for p-type microcrystalline Si layers leads to higher crystallinity and lower series resistance (resulting in 23.45% HIT cell on 4cm2). B. Legradic showed how the masking process for selectively depositing n-type nc-Si in n-type HIT cells leads to effective lifetimes above 4ms and efficiency of 25.0% (90cm2) and 23.3% (244cm2). C. Peng pointed out the importance of high Jsc for HIT cells, and higher crystallinity for optimized PH3 doped a-Si leads to 23.8%, with post treatment 24.3% on large area 6inch wafer.
In Area 5 “Nanoscale Characterization” covered a number of cross-cutting characterization techniques applied to different materials systems from polycrystalline thin films to high-efficiency III/V. Schulte and Bidaud both talked about how cathodoluminescence can inform process optimization. Stuckelberger showed how an x-ray beamline can be used to simultaneously make a number of measurements on polycrystalline solar cells. Xiao and Lanzoni illustrated what we can learn by mapping work functions with KPFM. Finally Bechu gave a detailed description of how XPS can be used to study both surfaces and the bulk of CIGS.
In Area 6 “Stability and Lifetime of Perovskite Solar Cells” R. Prasanna et al. demonstrated, for the first time, 1000 hr stability tests, including damp heat of low bandgap tin-lead perovskite solar cells, due to encapsulation in a glass/glass package with rubber edge seals and polyolefin encapsulant. S. Liu, et al. demonstrated record efficiency of 20.92% in flexible perovskite solar cells due to a DMS additive and EDTA modification of the SnO2 ETL that improve perovskite crystallinity and carrier dynamics while reducing trap density.

In Area 7 “Radiation Effects on Solar Cells” C. Pellegrino explained the physical causes of proton and electron-induced degradation to the Voc. Using a newly developed model it was possible to account for the change in dark-IV due to radiation. R. France showed promising results for InGasP as an alternate bottom cell for the inverted metamorphic multi-junction solar cell.

In Area 8 “System Performance and Models” Keith McIntosh of PV Lighthouse presented a ray-tracing approach to analyze the performance of bifacial systems. He showed how the SunSolve software uses cloud-based computation (2000 cores), micron-level tracing of 20 million rays and includes intricate effects such as cell texture, coupled with SPICE simulation of the module circuitry. He was able to quantify the mismatch losses in single-axis tracker systems with bifacial modules. The non-uniform backside irradiance due to edge brightening and torque tube shading can lead to 0.2% cell-to-cell mismatch loss on the modules, the actual value depending on the module position. Martin Waters from Cyprus Creek showed that including the effect of rear side irradiance to capacity test methods improves the consistency of results. Steve Ransome discussed using outdoor test data for analyzing accuracy of energy yield models using data.

In Area 9 “Mechanisms of Module and Cell Degradation” Robert Witteck presented work demonstrating improved UV stability of PERC cells through the use of different AR coatings. This is important since UV with wavelength less than 365nm is often transmitted through EVA encapsulation. A graded layer of SiNx, SiOy/SiNx, or a thermal oxide showed the best stability.

Area 9 - Accelerated testing for Cell, Interconnect, and Module Durability. Cell crack and solder bond degradation are major degradation mechanisms in the field and often accompanied by an increase of the series resistance. The session covered test procedures, modeling of the stress and detailed analysis of the field aged modules are presented. Bruckman provided comparison of field exposed and accelerated exposures of backsheets. 40 modules of 19 brands, 6 outer materials. Effects of water spraying, Xenon light, pollution, described. Field survey showed non-uniform BS degradation even in the same row of array. Jones provided a comparison of indoor and outdoor tests measured by the change of series resistance. IEC61215 TC200 / Qualification Plus TC500 tests were compared with outdoor exposures and clear correlations were observed. Increase in series resistance coincide with change in EL images. Saleh introduced a new analysis method (SSTDR) of PV arrays. Utilizes Injected electrical pulse reflected at impedance discontinuities. Disconnection, DH degradation, PID could be also detected. A. Sinha presented solder bond degradation of the field-aged modules in a hot and humid climate. The modules are studied and the increase of series resistance confirmed from bright spots appearing on the EL image.

In Area 9 “Accelerated Testing of Polymeric Module Materials” X-ray scattering results were presented for PET (core), EVA/PET/PVDF backsheet (including from a toughness study), AAA backsheet (including accelerated aged material), and PVDF-containing backsheet (including accelerated aged material) to identify changes in the crystalline structure. About 1,000 modules from the field were analyzed and the failure mode observed compared to fresh module failures observed in lab tests designed per climatic zones. Some similar results are observed, with temperature above 90C strongly increasing degradation rates. The previous MAST sequence was further developed with the goal of reducing the test duration from 9 months to 6 months. A variety of options were explored (including UV intensity, specimen temperature, and use of water spray) with examples shown for AAA and PVDF backsheet specimens. An empirical degradation model for Pmax was built including
Fitting one climate zone enables the prediction of the same module degradation rate in 2 other climate zones. A laminated coupon specimen construction, including bump and trench geometries, was demonstrated. The importance of artificial UV weathering was demonstrated relative to sequential application of thermal cycling, water spray, or damp heat testing. An empirical model for degradation prediction of unencapsulated cells. Two materials tested and shelf-life prediction estimated before encapsulation into a module.

In Area 11 “Solar Power Forecasting and Grid Integration” R. Perez showed how solar power can provide firm power at relatively low cost if state-of-the-art forecasts are used with over-sized PV power plants and energy storage. N. Engerer described how in Australia solar power forecasting on distribution systems is on the verge of being used operationally by distribution system operators for maintenance scheduling and management / operations. L. Visser compared multiple machine learning models. Several models were shown to have almost identical forecast ability indicating that the skill of machine learning models for solar forecasting seems to have saturated. Improvements in meteorological models are needed.

In Area 11 “PV Performance Modelling, Bifacial PV” Patel provided a valuable review of LCOE, albedo, and energy yield for the different seasons. Bailey evaluated different data sets with the numerous ground measurements; the review did not identify significant correlations. Ayala Pelaez provided a great talk discussing the impact of the torque tube on shading and power generation for bifacial single-axis tracked systems. Wang discussed a methodology that successfully predicted ramp rates at PV plants and suggested plant designs that consider wind direction for ramp rate mitigation. Habte described the current TMY and provided an introduction to a custom TMY data set that considers GHI and POA irradiance. Cormode presented on a method for improving the accuracy of energy estimates and found that the clear sky index method worked best.

**Area 11, “PV-Performance-Modelling, Bifacial PV” provided valuable reviews of LCOE, albedo, and energy yield.**
The women in PV session was very well-run, and nearly every seat was filled. A three-course meal was served first, allowing table mates to meet each other and network. Sarah Kurtz gave a keynote speech in which she shared her not-so-secret secrets to success that she had learned from her family and friends throughout life. It was an excellent talk that spurred many questions from young women in the audience for the question and answer session afterward.
In Area 1 “Novel architectures for improved opto-electronic performance” the winner of the poster prize was Julia D’Rozario, who presented a study of thinned GaAs solar cells using textured rear-side surface and mirror acting as a back-reflecter to enhance the 1 um absorber thickness. Envisioned as a potential solution for space applications, they studied the inclusion of both flat and random textured reflector in the quantum efficiency and IV behavior.

In Area 4 “Work Function Engineering” the poster award was given to G. Kaur for the amazing work on the use of ultrathin LPCVD SiN layers in passivating contacts. The key role of fixed charges in the interlayer in enhancing selectivity was demonstrated in a thorough analysis. Accurate characterization of the contact selectivity was performed which allowed to unveil this new phenomenon.

In Area 5 “Characterization” the best poster award went to Enrique Barrigon for work on “Nanoprobe Enabled Electron Beam Induced Current Measurements on III-V Nanowire Based Solar Cells”

In Area 7 “Space Photovoltaics” the poster presented by Lyndsey McMillon-Brown from NASA Glenn was awarded best poster in this Area 7, being one of the first analysis where Mars Rover mission solar array performance data (Opportunity) and experimental studies demonstrate the relationship governing energy generation when considering Mars settled dust on the surface of solar cells.

In Area 9 “Anti soiling coating and soiling losses” the best poster award went to K. Ilse for work on “Quantification of Abrasion-induced ARC Transmission Losses from Reflection Spectroscopy”

In Area 10 “Power Electronics and Microgrids for PV” Ramanathan Thiagarajan won the best poster award for work on “Effect of Reactive Power on Photovoltaic Inverter Reliability and Lifetime”