The garden outside the Convention Center and the building façade.

Monday is traditionally a day at the PVSC that has the highest profile talks by the international experts with the most exciting or most important points to talk about. This year was no exception. The day began with three outstanding plenary lectures by Harry Atwater (Cal Tech), Marika Edoff (Uppsala), and Stuart Wenham (SunTech).

Prof Atwater delivered a very interesting lecture on emerging paths to low cost high efficiency solar cells. It highlighted the strength of combining innovative light trapping and epitaxial lift-off processes for low-cost manufacturing of GaAs-based thin film and silicon nanowire solar cells. He reported record efficiencies as high as 27.6% (cells) and 21 % (modules) for thin film GaAs devices as well as large area silicon micro wire solar cells. He presented a discussion of some very interesting partial-radial junction solar cell devices showing very good performance and explained in detail their operation. He also discussed the use of a sulfur analog to the trioctylphosphine oxide (TOPO) compound commonly used in passivating semiconductor nanoparticles for passivation of GaAs.

Prof. Harry Atwater speaking during the plenary session.

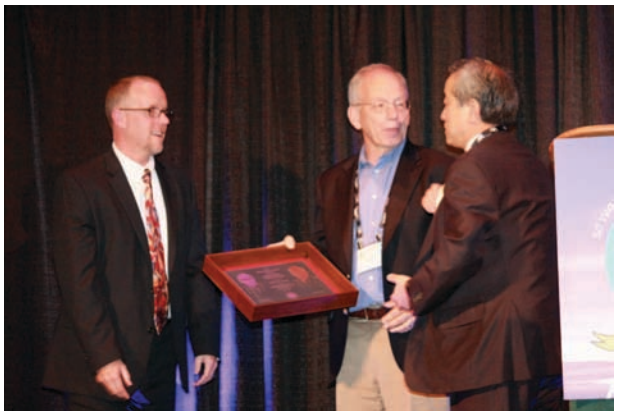
Marika Edoff presented highlights on $Cu(In,Ga)Se_2$ (CIGS) and $CuZnSn(S,Se)_4$ (CZTS) research. She noted that a very high efficiency device has been achieved on a polymer substrate by Tiwari and collaborators (18.7%), that a 15.7%-efficient large area module has been demonstrated by Miasolé, and that a 14.6% efficient module from a production line has been shown by Solibro. New buffer layers, to replace the traditional CBD-deposited CdS, were introduced, notably Cd and S free materials such as ZnMgO and ZnSnO, that yielded devices with ~18% efficiency. She discussed the use of dry processes such as ALD, ILGAR, and evaporation for producing these at rates sufficient for manufacturing. A study of the effect of gallium grading in the CIGS absorber was also presented. Differences in diffusion rates of Ga and In were described, leading to the high-low-high band gap profile in finished devices. Finally, it was shown that using Cu-poor and Zn-rich compositions was critical for obtaining good quality CZTS material, and avoiding secondary phases such as ZnSe.

Marika Edhoff presents her plenary talk on CIGS and CZTS.

Stuart Wenham described what allows PV production in China to grow faster than in other countries -- not the low cost of labor but the low cost of capital and the adoption of the best technologies from around the world. It was noted that seeded casting of single-crystalline ingots can yield higher quality material away from the edges of the casting than can be obtained in Czochralski (CZ) wafers due to the lower levels of oxygen contamination in the cast material. This was related to the coating of casting crucibles with Si_3N_4. The availability of off-the-shelf systems for casting and other processes is permitting very rapid scale up of the Si industry in China. He showed a graph that demonstrated how in the past seven years Si solar modules have grown from a very modest baseline to the point today where four of the top five manufacturers of photovoltaics are located in China. He described a typical example of the very high performance Si devices now being produced in China and how high rate low cost processing has reduced the device cost. A detailed discussion was provided on the emitter contact technologies used. Finally, it was stated that silicon modules will achieve $1/W prices by 2015 even allowing for manufacturer profit.

Stuart Wenham answers questions from the audience following his talk.

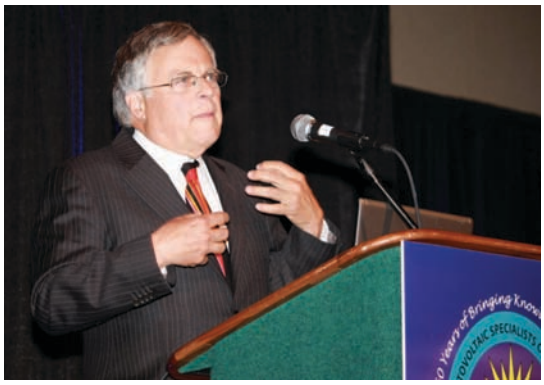
Following these plenary talks and a break for coffee, the keynote session included a mixture of award presentations and talks. Kicking off the keynote session, David Wilt, Conference General Chair, introduced the new IEEE EDS Fellows, Vladimir Mitin and Santosh Kruinec. These were followed by a historical perspective of photovoltaics for the past 50 years over which the PVSC has existed. Dr. Larry Kazmerski presented this talk including a wide spectrum of videos, interviews with important figures from the early days of the PVSC and a snapshot of the history of PV over the time the conference has existed. Prof. Masafumi Yamaguchi introduced this year's Cherry Award winner, Dr. Jerry Olsen of NREL. He was obviously very pleased to receive the award and thanked his team from NREL for their support and the community at large for its contributions. He gave an interesting speech on very high efficiency multijunction photovoltaics, which has been one of his primary contributions to the community. The talk was light hearted and historical but showed the dramatic progress that his group and others have made in recent years to the field of ultrahigh efficiency devices.



Jerry Olsen receives the Cherry Award

Rounding out the keynote session, Dick Swanson of SunPower presented a talk on the current status of PV, the economic drivers, and where the community stands in terms of cost of product. He argued strongly that past forecasts for future cost of devices had largely come true and that making similar forecasts for future cost reductions demonstrates that the crystalline Si community will reach cost targets that will leave them profitable when the investment tax credit expires in 2016. He reviewed current forecasts that suggest a slowdown in PV industry growth from the current 50% per year to more like 20% per year but that future growth would resume the high rate of expansion. He ended by noting that the global cumulative production of PV devices now tops 40 GW, that we used to talk about the day when we would reach 1 GW of production, and that now he looks forward to the day when cumulative production exceeds 1 TW.

The conference recessed for lunch and the past chairs of the PVSC who were in attendance gathered for a photograph. In the afternoon there were two sessions of oral presentations. Some of the highlights were as follows.



Dick Swanson presents his talk.

In Area 1 (Fundamentals and New Concepts), discussions focused on light trapping and antireflection coatings initially.

After the break Area 1 teamed up with Areas 3 and 7 for a joint session. R. Walters proposed a novel InP-based triple junction solar cell structure. Researchers showed that improvement of the InAlAsP top cell in multijunctions can lead to radiation-tolerant devices. Finally, talks presented data obtained at the Rochester Institute of Technology from devices grown in collaboration with Emcore whereby quantum dots were successfully incorporated into III-V absorber layers and showed increases in quantum efficiency at long wavelengths, below the range normally accessible to the devices.

Area 2 focuses on chalcogenide solar cells. In the early session A. Resigner described how Sn and Se losses can be reduced during post-deposition heat treatments of CTZSSe devices by the use of high partial overpressures of Sn and Se. Annealing in a $SnSe_2$ atmosphere was shown to yield devices with up to 6.1% efficiency. The talk went on to describe in detail the many second phases formed in CZTS when the samples are annealed. For example, samples annealed above ~350°C were shown to exhibit segregation of ZnSe to both the front and back of the layer. This was related to the stability of the

Jim Sites speaks on limitations to CdTe devices.

material as a function of temperature. M. Contreras discussed improved efficiencies for wide gap CIGSe solar cells based on higher process temperatures made possible by a new high temperature glass from Schott. The higher temperatures pronounced enhancement of V_{oc} for devices with an energy gap of <1.4eV. He also showed that higher performances can be obtained in wider energy gap devices compared to historical values using the new glass and process temperatures.

After the break Jim Sites discussed the prospects for improving the efficiency of CdTe solar cells and modules. He indicated the origins of efficiency losses when moving from an ideal CdTe device to lab cells and modules. Minority carrier lifetime and too low carrier concentrations were identified as the main reasons for V_{oc} losses in lab cells. In modules the main factors reducing I_{sc} are absorption in the CdS, transparent conductor and glass, whereas fill factor suffers mostly from distributed resistance in the transparent conductor, shunts, and weak diode regions. In the last part of the talk the advantages of a material producing a minority carrier mirror were discussed. This would reduce carrier loss at the back contact and could potentially significantly improve device voltage, yielding record efficiency devices. Sites noted that addition of Mg to CdTe at the back of the device could yield such a minority carrier mirror.

Myriam Paire describes her work on micro-CIGS cells.

Myriam Paire presented experimental results on micro-CIGS cells working in the high injection regime. She reported a linear increase of I_{sc} and V_{oc} with increasing light flux up to 2000 suns and 1000 suns, respectively. This resulted in an efficiency of 17% as compared to initial 13% (AM1.5) without concentration. The extracted minority carrier diffusion length was of the order of 4 microns at 100 suns.

Adam Krysztopa reported on defect characterization in $CuGaSe_2$. Using photocurrent methods (MPC and PITS) on samples in a coplanar geometry and space charge spectroscopic techniques (AS and DLTS) on Schottky junctions he was able to detect up to nine deep defect levels. A very good agreement was achieved between results obtained on single crystals and thin films. A Meyer-Neldel plot was shown to be a very useful tool for defect assignment. Advantages of using photocurrent methods were indicated. Zhang Xianfeng presented a high-angle angular dark field scanning transmission electron microscopy (HAADF-STEM) and high resolution TEM (HRTEM) study on $Ag(In,Ga)Se_2$ (AIGS). Segregation of Ag in a top

layer was detected. The poor quality of AIGS/CdS interface was proposed to be responsible for the low efficiency of the AIGS cells (7.9%).

Susanne Siebentritt listens to a talk

In her talk Ana Kanevce presented a simulation of CdTe solar cells. She investigated combined effects of minority carrier lifetime and carrier density variations in different parts of the junction. For regular uniform cells the efficiency was found to depend mainly on the lifetime. Increasing the doping at the back contact should lead to V_{oc} enhancement, in agreement with the earlier talk by Sites. It was predicted that such back contact engineering could lead to 18 % efficient devices with high tolerance for low minority carrier lifetimes in the highly doped layer.

In the crystalline Si Area 4 presentations, R. Brendel described a 21.7% efficient localized rear contact cell with Al_2O_3 passivation. For a device with a 43 micron thick front tunnel contact, produced by an epitaxial lift-off technique, a 19.1% efficiency was obtained. The quantum efficiency of the device was related to its thickness, and current losses were explained based on absorber layer thickness. R. Woehl, in an exceptional student presentation, described the achievement of a >20% Si solar cell with an Al-alloyed back contact, back junction cell geometry. Finally, K. Maki described a 58 micron thick "HIT" contact solar cell with a 747 mV open circuit voltage. These performances are all remarkable.

Standing room only in Area 9's afternoon session.

After the break, Area 4 focused on defects in Si. The presentation by Bertoni showed how, using XBIC, a resolution of 24 nm has been achieved. Photoluminescence (PL) mapping *in-situ* showed recombination at dislocations and metal precipitates. Schubert described a method for obtaining differential PL images that demonstrated the impact of Fe and Cr on the performance of devices fabricated from multicrystalline Si ingots. A more detailed mapping process was shown to demonstrate the distribution of boron-oxygen complexes, and the relative magnitude of active and metastable states after heat treatment. Das highlighted increasing defect activity in more advanced cell structures resulting in a loss of absolute efficiency of up to 1% in well-passivated structures. Modeling showed erosion of levelized cost of electricity for high efficiency cell concepts. Recent n-type bulk absorber doping results gave efficiencies of ~19.7%, corresponding to a 20.4% p-type cell. Ohmer described how circular focus laser annealing results in cracks during laser induced epitaxial regrowth of Si, while a line focus with appropriate control shows no defects generated with widths < 16 um for (100) and < 5

um for (111) Si. Zin described how stress in Si creates boron spots in SiO_2 and Si_3N_4 dielectrics, which are difficult to avoid. Other dielectrics need to be investigated.

Talks in the amorphous Si session (Area 5) included work by E. Johlin, which showed interesting results that reveal that stress and density in a-Si:H are universally controlled by the impacting ion momentum during plasma deposition. This was shown to be governed by the pressure of the plasma. H. Fujiwara described a complex ellipsometry technique and model that precisely characterizes textured solar cells *in-situ* on the production line. Meier discussed a unique optical measurement technique for obtaining *in-situ* thickness and microstructure of the a-Si:H films during growth using the plasma itself as the light source. M. Fischer described Raman measurements on Raman-active substrates, properly accounting for the substrate contribution. Finally, V. Dahal used ellipsometry over large areas to map the amorphous to microcrystalline transition as a function of process conditions and location.

Area 8 focuses on characterization of photovoltaics. G. Brown discussed spatially resolved methods for CIGS characterization with a very nice comparison between electroluminescence and electron beam induced current measurements that provided a direct method for separating local energy gap variations from local differences in minority carrier diffusion lengths. Li discussed the use of admittance spectroscopy to detect defect parameters as well as material properties including mobility and carrier lifetime for a wide variety of cell types. The measurement takes advantage of non-ideal admittance response to gain additional information about the device.

Area 9 focuses on modules and systems. In the early session**,** Michael Kempe gave us new insights in encapsulant chemistry, showing the relations between chemical features and physical properties of ethylene vinyl acetate (EVA) and several alternative encapsulate materials such as silicones, PVB, PEN, etc., focusing primarily on moisture, transmittance and UV stability in relation to durability. David Dumbleton presented a simplified Arrhenius equation to model ageing of PV modules. Jarnav Kanuga discussed polyethylene terephthalate (PET) degradation and how bond hydrolysis relates to temperature-induced degradation. Temperatures above 80°C were shown to be strongly related to increased aging rate. Peter Lehman presented historical results on a 20 year old PV array, with measurements taken in 1990, 1999, and 2010. This showed an exponential increase of degradation, resulting in a 16% power reduction over the age of

Past chairs of the IEEE PVSC attending the 37th PVSC

the array. The observation was probably the result of the harsh maritime environment and resulting corrosion in which the array operated. Gabi Friessen examined the actual power performance of 13 modules and six technologies, finding variable performance, especially in the thin film modules. Energy performance was also well modeled.

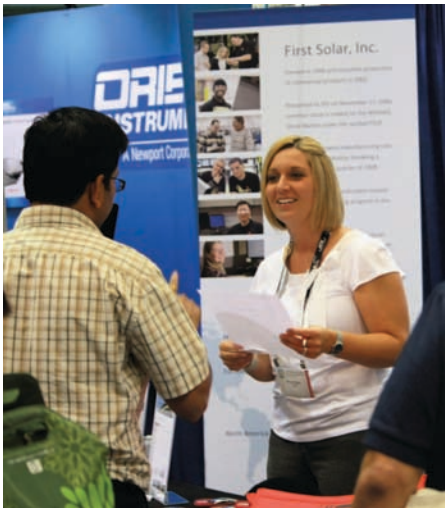
After the break, Detlev Heinemann presented an overview of PV forecasting methods, noting that a combination of methods would improve accuracy. The methods are cloud motion from satellite images, the persistence model, and the standard weather forecasting. Snow detection and fog detection would further improve accuracy. Sharif Aljoaba presented a new model on the light wavelength effects on the thermal electric properties of PV cells. By considering only the wavelengths absorbed by the cell, the temperature was modeled more accurately than by standard methods by up to 4%.

Elaine Ulrich speaks in Area 10 about interacting with US policymakers.

In Area 10 a series of presentations described national programs supporting photovoltaics.

At the end of the day participants relaxed at the exhibitor's reception. The exhibit this year has a very strong presence of instrument vendors and others with expertise in characterization tools and techniques. Some materials suppliers are also attending as are some national laboratories and other organizations. Only a few solar module manufacturers are represented this year. All of the exhibitors will be pleased if the conference attendees will stop by and visit with them at their booths. Monday evening the attendance at the exhibit was strongly motivated by the food and drink available in the exhibit hall.

-- Angus Rockett



First Solar's representative speaks with an attendee at the vendor show.