

Bay Area Photovoltaic Consortium

GCEP Annual Report 2014

Investigators:

Yi Cui, Associate Professor of Materials Science and Engineering, Stanford

Ali Javey, Assistant Professor of Electrical Engineering, U.C. Berkeley

Abstract

The Bay Area Photovoltaic Consortium (BAPVC) is conceived to create a vibrant forum for interaction among Photovoltaic (PV) industry and academic experts to address the critical challenges in converting the U.S. leadership in PV R&D into leadership in PV Manufacturing. The U.S. faces substantial challenges in building such a PV manufacturing base as many of our competitors benefit from fewer manufacturing restrictions, faster permitting processes, lower cost labor and substantial financial incentives. In this environment, U.S. manufacturing leadership must be built upon superior, more innovative technologies delivered at all stages of the value chain. The industry leaders who have founded the numerous PV start-ups or launched internal development in larger firms are highly creative people. Certainly they are guiding their own companies toward excellent results. Providing this input to guide additional research in universities will add significant value. However, great innovation is possible if this expertise is engaged interactively with their counterparts in the academic realm. BAPVC will provide the forum for great innovation.

Introduction

BAPVC is led by Stanford University and University of California Berkeley. BAPVC is funded by the U.S. Department of Energy with additional support from industry and universities. DOE is providing \$25 million over five years (2011–2016) as part of the SunShot Photovoltaic Manufacturing Initiative (PVMI) to provide a source of research funding for all universities across the United States.

BAPVC conducts industry-relevant research and development that will impact high-volume PV manufacturing, produce a highly trained workforce, and speed up commercialization of cutting-edge PV technologies. BAPVC will develop and test innovative new materials, device structures, and fabrication processes necessary to produce cost-effective PV modules in high volumes. The research aims to find technologies which can increase photovoltaic conversion efficiencies and simultaneously reduce manufacturing cost. Success in research is measured by transfer of the technologies for development in industry.

Background

The heart of the BAPVC is the Industry Board that includes all of the member companies. The Industry Board identifies research priorities, informs the scope of RFPs, reviews and ranks proposals, and monitors the progress of research. Industry members are the first to learn of inventions and will be in the best position, potentially in partnership with other member companies, to adopt and build on those inventions in their own laboratories and factories. In addition to GCEP members, current members include

Asahi Glass Company, Alta Devices, BASF, EpiSolar, HelioVolt, Stion, Total American Services, and 3SUN.

BAPVC launched thirty five projects which are coordinated in the following thrusts: 1) High performance and multijunction cells; 2) Silicon absorbers and cells; 3) Thin film absorbers and cells; 4) Photon management and transparent conductors; and, 5) Encapsulation and reliability.

The high performance and multijunction thrust explores new growth processes, material systems, and device architectures offering high device efficiencies at low processing costs. In particular, two parallel approaches are being explored, one relying on reducing the processing costs of III-V single junction solar cells and the other exploring tandem device architectures based on Si bottom cells. The highest performance for single-junction cells, currently at 28.8% efficiency, has been demonstrated in III-Vs. However, their module costs have been estimated by NREL to be currently >10x of those of Si cells. This high cost mainly arises from the initial substrate and epi-growth by the MOCVD process. Thus, BAPVC is developing disruptive growth and processing technologies that will drastically lower the cost without sacrificing the device efficiencies. The second path is exploring tandem cells based on Si (or CIGS, CdTe, or III-V) bottom cells to enhance the efficiency of the existing PV technologies. Cost analysis, device modeling, and experiments are being performed in parallel in a collaborative manner to ensure success. The projects are shown in Table 1.

Table 1. High Performance and Multijunction Cells Thrust

Ali Javey	Berkeley	High Performance, Low Cost, III-V Photovoltaics on Metal Foils
James S. Harris	Stanford	Ultra high efficiency thin film multi-junction solar cell
Paul McIntyre	Stanford	Thin Film Compound Semiconductor Solar Cells via Templated Growth
Michael McGehee	Stanford	Low-Cost Tandem Solar Cells With Greater than 20% Power Conversion Efficiency
Eli Yablonovitch	Berkeley	High Voc Solar Absorbers for High-Efficiency, Spectral-Splitting, Solar Cells
Y.-H. Zhang	ASU	Si/II-VI double-heterostructure solar cells
Tonio Buonassisi	MIT	Design principles and defect tolerances of silicon / III-V multijunction interfaces
Peter Bermel	Purdue	Exploratory Photovoltaic Modeling and Simulation

Silicon-based solar cells are the dominant PV technology today with more than 80% market share. While the Si cost component has been decreasing steadily (from over 40% to 19% over the last decade) it is still a significant cost at the module level. Thinner Si cells can reduce the module cost further and leverage the potential higher efficiency and form factor to reduce balance-of-system costs. In this thrust, the key problems which are being addressed to enable high volume manufacturing of high efficiency Si cells include: 1) Commercially viable manufacturing of thin crystalline Si below 50um; 2) Passivation of thin crystalline Si to meet the high efficiency targets; 3) Absorption of all available

light within a reduced absorber volume; and, 4) Metallization and packaging of thin Si cells into lightweight modules. Project in Silicon are shown in Table 2.

Table 2. Silicon Absorbers and Solar Cells

Yi Cui	Stanford	High Efficiency Ultrathin Silicon Solar Cells
Sanjay Banerjee	Texas	Thin Crystalline RPCVD Back Contact Cells
Stuart Bowden	ASU	Laser Wafering
Maikel van Hest	NREL	Module Interconnects and Crystalline Film Silicon by Atmospheric Pressure Processing
Vivek Subramanian	Berkeley	High-resolution, high-speed printing of PV contacts

Thin Film PV technologies are now established in commercial markets. As the global market continues to expand, the competitiveness of thin film solutions faces four significant Grand Challenges: (1) increasing efficiency of modules; (2) reducing direct materials costs; (3) reducing capital intensity of manufacturing; and, (4) design and validation for long-term field reliability. BAPVC projects in thin film photovoltaics are shown in Table 3.

Table 3. Thin Film Photovoltaics

Bruce Clemens	Stanford	Bandgap Grading in $\text{Cu}_2\text{ZnSn}(\text{S},\text{Se})_4$ Solar Cells
Stacey Bent	Stanford	SnS based Photovoltaics
Michael Toney	SLAC	Advanced Materials Characterization
Greg Hanket	Delaware	Advanced Evaporation Source Design
Hugh Hillhouse	Washington	Development of Multicolor Lock-in PL Method
Scott Dunham	Washington	Fundamental Modeling of Chalcopyrite Solar Cells
Mark Lonergan	Oregon	Identifying Problem Areas in CIGS and CdTe Based Photovoltaic Devices
Colin Wolden	CSM	Non-Equilibrium Processing of CdTe Absorbers
Mike Scarpulla	Utah	Laser Processing CdTe: Efficiency & Manufacturing
Chris Ferekides	USF	CdTe Absorbers
Delia Milliron	LBNL Texas	In situ characterization of grain growth in thin film semiconductors
Peidong Yang	Berkeley	Applying Cation-Exchange Chemistry to Nanowire Arrays for Efficient Solution-Processed Solar Cells

The Photon Management and Transparent Conductors thrust attacks several grand challenges including: 1) develop materials and structures to couple maximum sunlight into the solar cells and to control the above bandgap photon distribution for complete absorption with significantly reduced absorber materials; 2) use photon management to enhance the solar cells parameters including short circuit current and open circuit voltage; 3) Develop low-cost highly transparent (~95%) and low sheet resistance electrodes (<5 ohm/sq) for solar cells with n- and p-type contact capability; and, 4) develop processes to

implement the above materials and structures in practical, scalable solar cell manufacturing.

Table 4. Photon Management and Transparent Conductors

Mark Brongersma	Stanford	Percolating Transparent Metallic Electrodes for Solar Cells
Shanhui Fan	Stanford	Theory and simulation of photon management in nanostructured solar cells
Wladek Walukiewicz	LBNL	Ideal Transparent Conductors for Full Spectrum Photovoltaics
Joel Ager	LBNL	New P-type Transparent Conductors
Harry Atwater	Cal Tech	Solar Cell Efficiency Enhancement via Light Trapping in Resonant Dielectric Sphere Arrays
Kaustav Banerjee	U.C.S.B.	Graphene Electrode Eng. for Photovoltaic Application
Ning Wu	CSM	Large-Area, Fast, and Electric-Field Assisted Continuous Coating for Nanostructured Photon Management

The impact of high-volume and cost-effective PV technologies depends critically on their reliability and durability over extended operating lifetimes. Successful commercialization also requires accurate PV lifetime predictions and related product warranties. Ironically, despite optimistic forecasts for the impact of cost-effective PV technologies, uncertain degradation mechanisms, the lack of testing metrologies, poor accelerated testing protocols, the almost complete lack of science-based kinetic degradation models, and uncertain lifetimes currently present significant barriers for success. BAPVC’s projects to address these issues are listed in Table 5.

Characterizing the stability and reliability of PV materials, including barrier-films and encapsulants, is necessary not only to design accelerated testing protocols to standardize PV module requirements, but also to provide the fundamentals for the design of improved PV materials and product designs. The encapsulation and reliability thrust attacks these barriers to develop understanding of the coupled thermo-mechanical, electro-chemical, and photo-chemical degradation mechanisms that determine the reliability and operational lifetimes of PV technologies.

Table 5. Reliability, Encapsulation & Barrier layers

Reinhold Dauskardt	Stanford	Reliability and Operational Lifetimes for BAPVC Technologies
Roger French	Case Western	PV Module Performance & Lifetime Prediction: Inserting New Technologies Without Lifetime Penalty
Rachel Segalman, Jeffrey Urban	Berkeley	Novel polymer-nanocrystal composite barrier layers
Bernard Kippelen, Samuel Graham	GIT	Tailoring Electrostatic Interactions to Produce Hybrid Barrier Films for Photovoltaics

Results

BAPVC holds meetings bi-annually to stimulate interaction among the industry members and researchers. These were held May 6-7, 2013 at Stanford and November 18-19, 2013 at Berkeley. We also prepared a full report of progress and plans for future work that is available in the Bay Area Photovoltaic Consortium Project Catalogue 2014. Here we will describe some of the most significant highlights from a few of the projects.

Low-Cost Tandem Solar Cells With Greater than 20% Power Conversion Efficiency

McGehee's group at Stanford is studying a new class of materials with potential to increase performance of commercial photovoltaic modules without a great increase in production cost. Hybrid tandem photovoltaics, two different semiconductor technologies used in a single tandem device, can improve the efficiency of solar modules without greatly increasing the module cost. Recent rapid progress in a new type of solar absorber, perovskite solar cells, also opens the opportunity to use these in hybrid tandem cells. 4-terminal hybrid tandems require a semi-transparent top cell. Typically, a perovskite solar cell is opaque because it is completed by the thermal evaporation of a metal back electrode, either Au or Ag, on the order of 100nm thick. To enable the transparency required to make a 4-terminal tandem, they have replaced this opaque electrode with a silver nanowire (AgNW) mesh that has a low sheet resistance and high transmission. The semi-transparent device is nearly as efficient as its opaque Au electrode counterpart as shown in Figure 1. Their semi-transparent cell, at 11.6%, is much more efficient than other research-stage solid-state thin film solar cells, with the best semi-transparent bulk heterojunction cell at 5.0% and the best semi-transparent solid-state dye cell at 3.6%. The small decrease in photocurrent even without the back reflector speaks to the strongly absorbing nature of the perovskite material. Notably, the series resistance of the semitransparent device matches that of the control device with an opaque thermally evaporated Au electrode. The transmission through the semi-transparent device peaks at 73% around 800nm, the center of the critical 600-1000nm transmission window. Uniquely, this semi-transparent device has both a high transmission and a high efficiency.

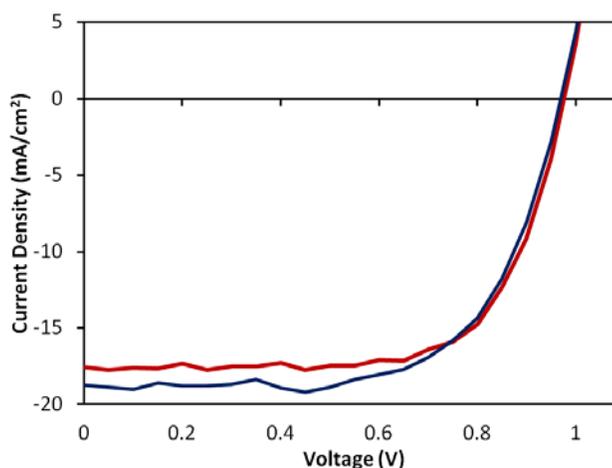


Figure 1. IV curves comparing best opaque vs. semi-transparent perovskite devices.

They show that they can improve even a state-of-the-art CIGS by placing it in a hybrid tandem. They improve a CIGS cell from 16.7% alone to 17.1% in a tandem Table 6, to their knowledge the highest efficiency for a 4-terminal multijunction polycrystalline solar cell reported in literature.

Table 6. Performance metrics of semi-transparent perovskite cell, unfiltered CIGS cell, CIGS cell filtered by the perovskite cell, and the resulting 4-terminal tandem efficiency.

	J_{sc} (mA/cm ²)	V_{oc} (mV)	FF (-)	Efficiency (%)
Perovskite	16.8	977	0.704	11.6
CIGS - Unfiltered	30.9	694	0.78	16.7
CIGS - Filtered	10.3	667	0.80	5.5
4-Terminal Tandem				17.1

High Performance, Low Cost, III-V Photovoltaics on Metal Foils

Javey’s group at Berkeley focuses on understanding and characterization of the thin-film vapor-liquid-solid (TF-VLS) growth technique as a low-cost process technology for III-V thin film solar cells on metal/glass substrates. In the last review period, they have focused on understanding and controlling the nucleation events of TF-VLS InP. Furthermore, optoelectronic characterization of the grown InP has been performed in depth to shed light on the potential PV efficiencies that may be feasible to obtain using this growth technique. Collaboration with Purdue, also supported by BAPVC, has been initiated to further understand the material performance limits of TF-VLS InP. Finally, in collaboration with NREL, another BAPVC partner, a preliminary cost model has been developed.

Recently, a method for growth of ultra-large grain (>100 μ m) thin-films on non-epitaxial substrates was developed by their group via the thin-film vapor-liquid-solid growth mode as shown in Figure 2a. The resulting poly-crystalline films exhibit similar optoelectronic quality (Fig. 2b,c) as their single-crystal counterparts.

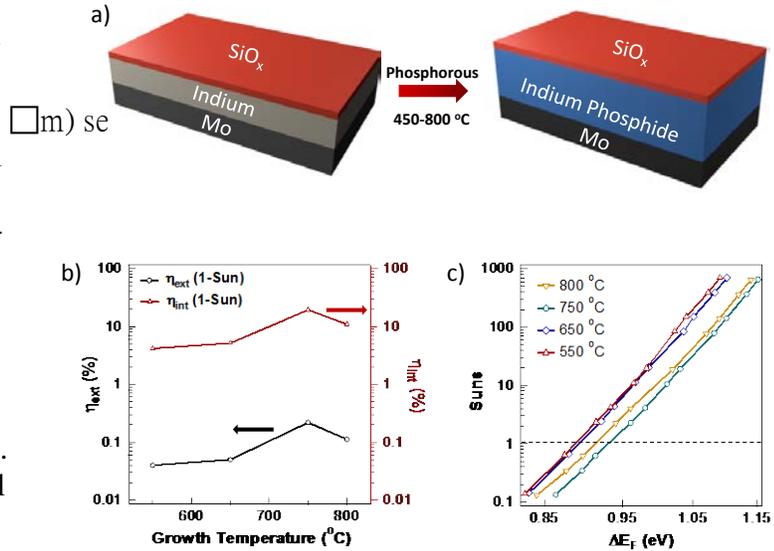


Figure 2: Growth method and optoelectronic characterization. **a**, Schematic view of the thin-film VLS growth technique for planar InP films. **b**, Measured external luminescence efficiency and extracted internal luminescence efficiency as a function of growth temperature. **c**, Optically measured “I-V” curves obtained from external luminescence efficiency measurements. Here, Suns represents the intensity of the absorbed laser light (1-sun = 100 mW/cm²), and corresponds to the photogenerated current level. The quasi-Fermi level splitting (ΔE_F) represents the resulting V_{oc} that would occur to balance the photogenerated current.

High Efficiency Ultrathin Silicon Solar Cells

Ultrathin monocrystalline Si cells offer the potential of saving materials, increasing manufacturing throughput, and enabling easy low-weight installation. The Cui group developed wafer-scale free-standing ultrathin monocrystalline Si fabrication with uniform thickness from 10 to sub-2 μm by KOH chemical etching. These ultrathin Si films exhibit excellent mechanical flexibility and bendability.

To demonstrate their processability in solar cell applications, the Cui group fabricated planar and double-sided nanotextured solar cells on these free-standing ultrathin Si films. Furthermore, they also experimentally demonstrated a large light absorption enhancement by a double-sided surface nanotexture design on the free-standing ultrathin Si films. With the front-side nanocone array designed for broad-band antireflection over the entire usable solar spectrum and the back-side pattern designed for light trapping roughly in the 800–1100 nm wavelength range, light absorption in 3 μm thick Si film is largely enhanced with a 130% increase in J_{sc} , achieving 58% absorption of the above bandgap sunlight. 7 μm thick Si can absorb 86% of the above bandgap sunlight.

Despite the exciting success of nanoscale texturing in light trapping, the power conversion efficiencies of nanostructured Si solar cells, however, remain below 19% for thick devices and below 11% for thin devices. The Cui group fabricated a sub-10- μm -thick Si solar cell with a 13.7% power conversion efficiency which utilizes all-back-contact design to overcome the critical problems of nanostructured devices: Auger and surface recombination. In general, nanostructured solar cells have a highly doped emitter

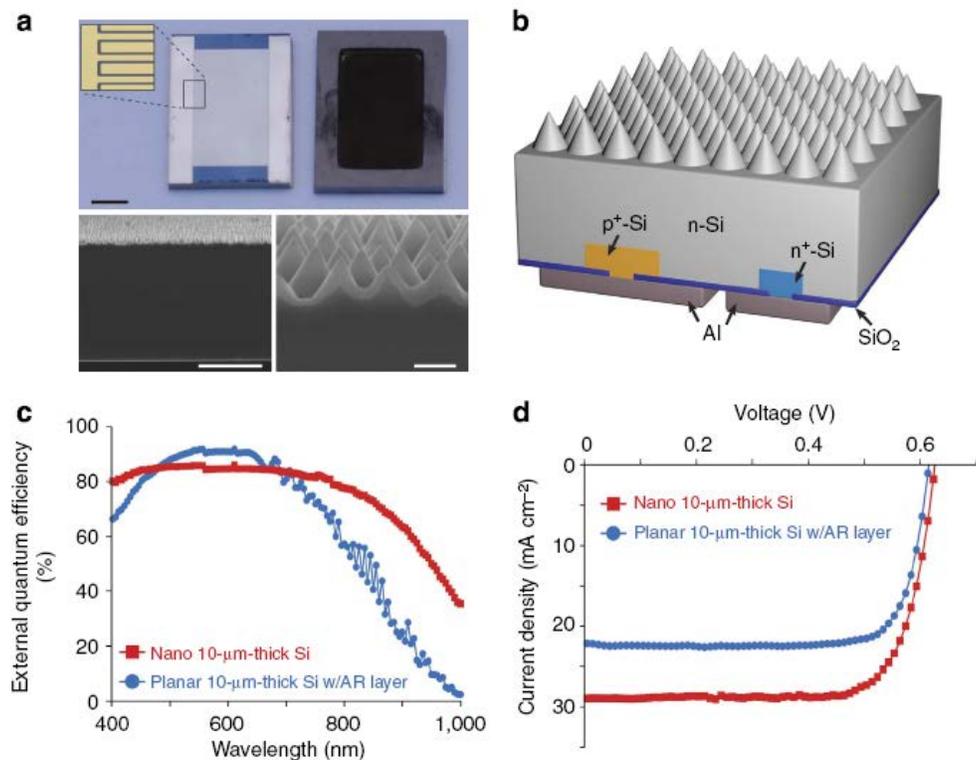


Figure 3. Ultra-thin Si nanocone solar cell. (a) Optical image and SEM cross-sectional views of the 10- μm -thick Si solar cell. (b) Schematic illustration of the device. (c) EQE data of the device and a planar control. (d) J-V characteristics of two devices in c.

layer at the front, fabricated by high-temperature diffusion processes. Because the diffusion profile of the dopants is dependent on the surface morphology, a nanostructured device tends to have a much deeper junction depth with a higher concentration compared with a planar device. It leads to severe Auger and surface recombination of charge carriers. Another problem of nanostructured Si solar cells is the increased surface area. Considering the fact that the surface recombination becomes more critical to device performance as the absorber becomes thinner, the increased surface area in a thin Si solar cell can lead to a severe decrease of efficiency. The Cui group designed devices with two main advantages: the all-backcontact design and the nanocones. Its all-back-contact design prevented Auger recombination loss near the front (see Fig.3), and its nanocone structure minimized the increase in surface area while enhancing the light absorption significantly. As shown in Fig. 3, it demonstrates over 80% EQEs at wavelengths from 400 to 800 nm.

Ideal Transparent Conductors for Full Spectrum Photovoltaics

Walukiewicz's group at Lawrence Berkeley National Laboratory has developed high mobility Cadmium oxide (CdO) thin films using conventional radio frequency magnetron sputtering methods on low cost glass substrates with electrical and optical properties comparable to films grown by pulsed laser deposition on sapphire. Optimized CdO films suitable for full spectrum PVs with resistivity in the mid 10^{-5} Ω -cm and $>85\%$ transmittance in the range of 400-1300 nm were achieved. The group also explored alloying CdO with MgO with the energy gap of 7.8 eV to upward shift the absorption edge and improve the UV transmittance of the resulting CdMgO alloys.

Previously the group has demonstrated high mobility Cadmium oxide thin films using pulsed laser deposition (PLD) method. In the past year, they have achieved CdO films with similar electrical and optical properties using scalable RF magnetron sputtering methods on low cost glass substrates. Fig. 4 shows the electron mobility of undoped and doped (In and Ga) CdO films deposited on glass using the RF sputtering technique. Sputtered deposited films on glass substrate with electron concentration up to 10^{21} cm^{-3} and mobility approaching $200 \text{ cm}^2/\text{Vs}$ ($\rho \sim 4 \times 10^{-5}$ Ω -cm) have been achieved.

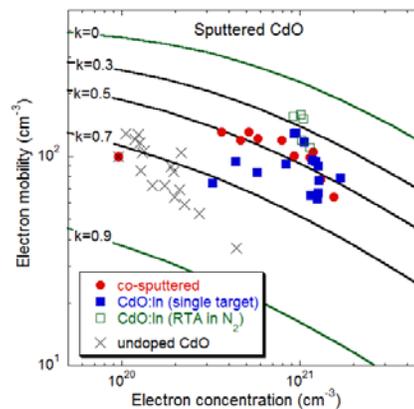


Figure 4. Electron mobility of sputter-deposited CdO films undoped and doped with In and Ga on glass substrates. Calculated mobilities of CdO with different compensation ratio k are also shown.

A drawback of these CdO based TCOs is their relatively small bandgap that limits the ultraviolet (UV) transmittance edge to only ~ 400 nm that is not sufficient for an efficient utilization of the UV part of the solar spectrum. The UV absorption edge of the doped CdO is determined by the intrinsic direct gap of ~ 2.2 eV and the Burstein-Moss shift associated with the high location of the Fermi energy in the conduction band resulting

from the large concentration of electrons in the material. In the past year, the group has also explored alloying CdO with MgO that has a much larger energy gap of 7.8 eV. They have synthesized and characterized a series of $\text{Cd}_{1-x}\text{Mg}_x\text{O}$ thin films with substitutional Mg content x up to 0.28 by co-sputtering from CdO and MgO targets. The synthesized material shows significant decrease in the grain size with increasing Mg concentration. The reduction of the electron concentration and mobility in these undoped samples was explained by a rapid upward shift of the conduction band edge with increasing Mg concentration. Alloying ~10% of MgO with CdO increases the intrinsic bandgap by ~400 meV resulting in a desirable shift of the optical absorption edge to higher energies, as shown in Figure 5. However, a significant reduction of electron mobility to ~20 cm^2/Vs was also observed. CdMgO films (~6% Mg) with electron concentration of $10^{21}/\text{cm}^3$ and mobility of 40 cm^2/Vs were achieved with In doping and thermal annealing. The films properties are comparable to standard TCOs and the relatively low mobility results in strong IR absorption. Hence, it was concluded that alloying CdO with MgO is not an appropriate route for achieving a TCO for full spectrum PVs.

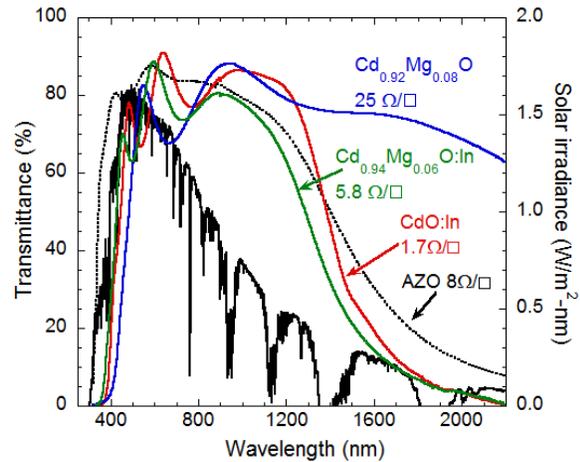


Figure 5. Transmittance of CdMgO films undoped and doped with In. Transmittance curves from a conventional Al doped ZnO (AZO) and a In doped CdO film are also shown.

The group has identified several areas that are essential for the further development of CdO based materials as transparent conductors for full spectrum PVs. The group has previously shown that the structural mismatch between ZnO and CdO creates two distinct regimes of optical and electrical behavior of $\text{Cd}_x\text{Zn}_{1-x}\text{O}$ alloys. The wurtzite phase alloys exhibit a reduction in the absorption edge energy across the visible spectrum from 3.3 to 1.9 eV with x increasing from 0 to 0.69. A phase transition to the rocksalt structure is observed above $x=0.69$, along with an abrupt step-like increase in the electron mobility up to 90 cm^2/Vs and an intrinsic gap to 2.6 eV. They are conducting systematic studies of the rocksalt CdZnO phase regime as these materials offer a potential of larger intrinsic optical gap without any detrimental effect on the electrical properties.

Reliability and Operational Lifetimes for BAPVC Technologies

The Dauskardt group developed scalable metrologies to characterize the coupled thermo-mechanical and photo-chemical degradation mechanisms of photovoltaic encapsulation systems. The effects of operating environments, including mechanical stress, flexing and bending, thermal cycling, temperature, moisture, and in-situ UV light were investigated.

A single cantilever beam (SCB) testing technique was developed to quantify debonding in backsheets and encapsulants. The debond energies of encapsulants (EVA, PVB) and backsheets (TPT-PVF) were measured as a function of temperature. The kinetics of encapsulant and backsheet interfacial debonding were characterized as a function of mechanical stress, relative humidity, and environmental temperature. To elucidate the mechanisms of environmental debonding, a viscoelastic fracture-kinetics model, which provides the basis to assess long-term encapsulant and backsheet stability, was developed and validated.

Using the newly developed SCB technique, the Dauskardt group measured—for the first time—the debond energy, G_c , of the EVA-Glass interface, shown in Figure 6, which decreased linearly with environment temperature, T , from 2.25 to 1.8 kJm^{-2} in the 20 to 50°C range. At temperatures close to the T_m of EVA(60°C), the value of G_c decreased abruptly (six-fold) to 0.3 kJm^{-2} . The values of G_c of the PVB-Ti interface (0.6 to 0.5 kJm^{-2}) were much lower than those of EVA-Glass in the same temperature range, and only slightly higher than those of EVA-Glass at high temperature ($T > T_m$).

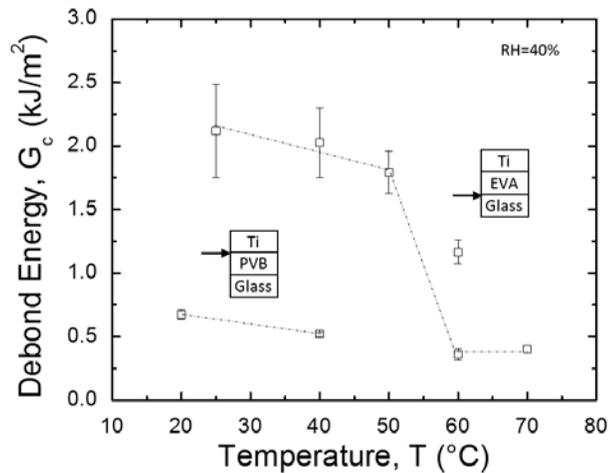


Figure 6. Debond Energy of EVA-Glass and PVB-Ti interfaces as a function of temperature. The debond experiments were conducted using the single cantilever beam technique in a chamber of controlled environment at 40% relative humidity.

Future Plans

BAPVC selected the initial sub-awards on the basis of the individual merit of the ideas and capabilities of the proposing teams. As work advanced, we have identified additional specific technologies that can support the BAPVC technologies accelerating progress toward industrial adoption. During the coming year we will fund this next phase of research through competitive procurement. This Request for Proposals aims to fund additional research to support BAPVC’s core technologies either by increasing the level-of-effort or duration of existing projects or by funding new projects addressing topics needed to accelerate progress of the existing technologies toward industrial adoption.

Patent Applications

“Transfer lamination technique for silver nanowire transparent electrodes”,
Grey Christoforo inventor, McGehee group.

Contacts

John P. Benner, Executive Director BAPVC, jpbenner@stanford.edu