Bay Area Photovoltaic Consortium

GCEP Annual Report 2015

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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, universities and GCEP. 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 First Solar, Alta Devices, BASF, EpiSolar, 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 $Cu_2ZnSn(S,Se)_4$ 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	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
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 12-13, 2014 at Stanford and October 6-7, 2014 at Berkeley. We are currently preparing a full report of progress and plans for future work that is available in the Bay Area Photovoltaic Consortium Project Catalogue 2015. Here we will describe some of the most significant highlights from a few of the projects.

A 2-terminal perovskite/silicon multijunction solar cell enabled by a silicon tunnel junction:

In an exciting example of collaboration among several BAPVC research teams, research to develop a top-cell partner for silicon solar cells delivered a first-of-a-kind tandem solar cell. The publication[1] in Applied Physics Letters was cited for "the most read this month" in January 2015. Led by Michael McGehee from Stanford and Tonio Buonassisi from the Massachusetts Institute of Technology, the team addressed what is recognized as the most important challenge for next-generation photovoltaics. Silicon based photovoltaic modules constitute about 90% of the total solar electric energy market. Solar-to-electricity conversion efficiency is the technical variable that most strongly influences silicon (Si) photovoltaic (PV) module costs. The record efficiency of crystalline silicon (c-Si) single-junction PV devices has only increased from 25% to 25.6% during the last fifteen years, asymptotically approaching the 29.4% Auger-recombination-constrained Shockley-Queisser limit. To make PV modules with higher efficiency than market-leading c-Si while leveraging existing c-Si manufacturing capacity, Si-based tandem approaches have been proposed. The top sub-cell in a silicon-based tandem should have a band gap between 1.6 and 1.9eV. However, very few materials exhibit high open-circuit voltages (V_{OC}) within this band gap range. Recently, the methylammonium-lead-halide perovskite has demonstrated a rapid efficiency increase with a VOC of 1.15 V. The methylammonium-lead-halide perovskite has a tunable band gap, ranging from 1.6 to 2.3eV depending on halide composition, though not all compositions are currently stable under illumination. Methods to optically transmit longer-wavelength light through a top perovskite sub-cell in a mechanically stacked tandem configuration have been developed recently.

A perovskite/Si multijunction solar cell may also be constructed via monolithic integration where a thin film perovskite sub-cell is deposited directly onto the c-Si sub-cell. Monolithic integration requires electrical coupling between sub-cells and transmission of infrared light to the bottom sub-cell. The BAPVC team used an interband tunnel junction to facilitate electron tunneling from the electron-selective contact of the perovskite sub-cell into the p-type emitter of the Si sub-cell. This approach stands in contrast to the recombination layer used in other perovskite tandem systems and is the one widely used in III-V and micromorph (a-Si/c-Si) tandem solar cells. Unlike the tunnel junction in III-V multi-junction solar cells, the tunnel junction for connecting the perovskite cell is made of silicon with an indirect band gap, enabling electrical coupling with minimal parasitic absorption. The conduction-band alignment between Si and the perovskite sub-cell's electron-selective contact (TiO2) enables bypassing the usage of a transparent conducting oxide (TCO) recombination layer, an alternative option with greater parasitic absorption.   This work used the methylammonium-lead(II)-iodide perovskite (CH3NH3PbI3), which has a 1.61eV band gap. The schematic, micrograph and band structure are shown in Figure 1.

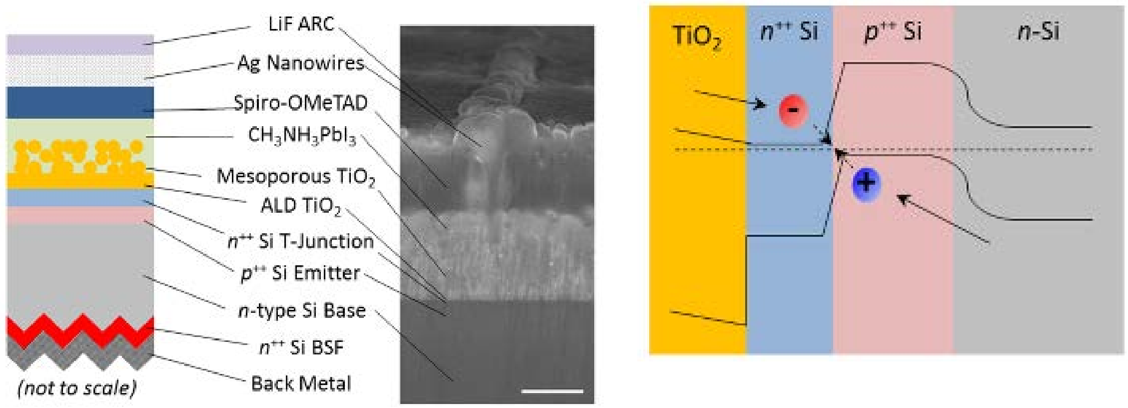

Figure 1. The device structure of a 2-terminal monolithically grown perovskite/Si multijunction solar cell with an n-type Si base. The polished SEM image is taken at 45 tilt to show the Ag nanowire mesh (500nm scale bar). Band diagram of the perovskite/silicon cell interface showing the charge-transport mechanism around the Si tunnel junction.

Rapid Thermal Processing of ZnTe:Cu Contacted CdTe Solar Cells:

Cadmium telluride (CdTe) is a leading absorber for thin-film solar cells. However, state-of-the art open circuit voltages (Voc) of CdTe thin film solar cells fall ~350 mV below the value expected based on the band gap of CdTe. One of the reasons is due to barriers at the back contact. A BAPVC Team at Colorado School of Mines headed by Colin Wolden has developed a process for forming the back contact that employs rapid thermal annealing to form a ZnTe:Cu contact.   This process precisely controls the activation and distribution of copper.   A 30 s annealing steps significantly improve fill factor and Voc without compromising the current density. Devices with >14% efficiency and >825 mV Voc are obtained under optimal conditions.

It is notoriously difficult to make good ohmic contact with CdTe using conventional metals, because this requires a work function of greater than 5.7 eV. The most common method to solve this problem is by etching the CdTe surface to make its surface heavily p-doped and contacting it with a buffer layer before metallization. Wet chemical etching using solutions such as Br2/methanol or nitric acid/phosphoric acid mixtures are most common. An alternative preparation is through ion beam milling, which also produces a Te–rich surface. Copper-doped zinc telluride (ZnTe:Cu) is one of the most commonly employed buffer layers. ZnTe was identified due to its valence band alignment and compatibility with CdTe. Copper is commonly used to degenerately dope this layer, which narrows the barrier width and permits electron tunneling, creating a quasi-ohmic contact. First Solar has integrated ZnTe:Cu into its product line, crediting this layer for improvements in both champion cell efficiency and module reliability. Small amounts of copper are also beneficial for doping CdTe. However the free carrier concentration is typically several orders lower than the total Cu concentration, suggesting that significant charge compensation takes place during Cu incorporation. Excessive copper has also been implicated in the formation of deep level defects, which have been correlated with reduced carrier lifetimes. Copper is highly mobile, and has been observed to preferentially accumulate at both the back contact interface and in the CdS window layer after thermal processing. With copper having both positive and deleterious effects it is critical to precisely control both its amount and spatial distribution in order to obtain high efficiency.

The most common approach to apply ZnTe:Cu is through thermal evaporation or sputtering at elevated temperature. A typical process in research laboratories employs temperatures between 240 - 360 ºC, and process times on the order of hours which accounts for sample heating, deposition, and cool down. The amount of copper introduced is controlled by either the target composition (1 – 5 wt %), or by using a fixed composition and altering the total thickness of the buffer layer. One drawback of this procedure is that deposition and diffusion occur simultaneously, with substantial diffusion continuing to occur during the subsequent cool down. The BAPVC team developed an RTP-based process for back contact preparation that de-couples Cu deposition from its re-distribution. The ZnTe:Cu back contact is co-evaporated at low temperature, with little or no interdiffusion. The sample is then subjected to short RTP treatment(s) to activate the junction.

Figure 2 shows I-V curves of four representative devices exposed to different RTP treatments. The original sample was the as-deposited device which wasn't treated by RTP. The as-deposited device showed good current collection, but the open circuit voltage was only 676.3 mV. In addition, the sample showed significant roll-over, which attributed to the presence of barriers at the back contact. The highest efficiency device was obtained after subsequent RTP treatments at 320/330 ºC. In this case the Jsc value remains essentially unchanged, but the VOC and FF increase significantly to 826.4 mV and 71.1 %, respectively, and the rollover in the J-V was eliminated. Very similar results could also be obtained from devices processed using just one 30 s RTP step, and here it was found that a setpoint of 360 ºC provided optimal results. Finally the device treated at 450 ºC is characteristic of overcooked samples. Here all the parameters decreased significantly, and it is inferred that Cu had diffused to the CdS layer, degrading the quality of the junction and leading to shunting.

The team at Colorado School of Mines demonstrated that thermal evaporation combined with RTP processing is an effective approach for fabricating back contacts for CdTe solar cells. RTP provides low thermal budgets and precise control over time-temperature trajectories, which is very applicable to CdTe solar cell fabrication. The work showed that the fraction of Cu in the ZnTe buffer was critical, but its initial distribution or the thickness of the buffer layer was not critical. Sequential RTP treatments were refined to optimize the process. By using appropriate RTP treatments, the efficiency of the devices increased from about 9% to 14.5%, increasing the Voc to >825 mV.

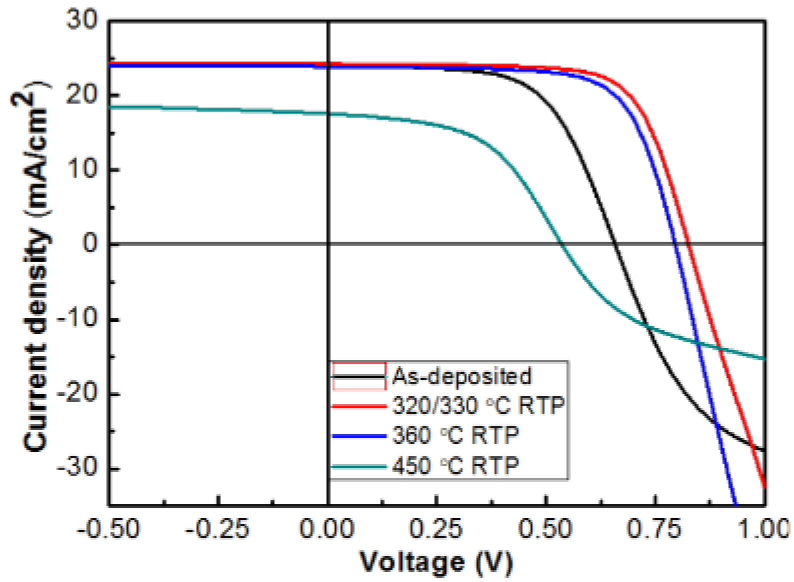

Figure 2. J-V curves of devices with different RTP treatments

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 as selected through a competitive procurement in 2014. These new projects will 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.

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PI: Colin Wolden
Colorado School of Mines

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University of Delaware

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Massachusetts Institute of Technology

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Stanford University

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PI: Harry Atwater
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