

# Bay Area Photovoltaic Consortium

## GCEP Annual Report 2017

### 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) 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 that can increase photovoltaic conversion efficiencies and simultaneously reduce manufacturing cost. Transfer of the technologies for development in industry is a primary metric of success in research. In short, BAPVC conducts research and development in universities to produce technologies that industry members will use.

### Introduction

BAPVC is a consortium led by Stanford University (SU) and University of California Berkeley (UCB) joined by three leading DOE labs—Lawrence Berkeley National Laboratory, SLAC National Laboratory, and the National Renewable Energy Lab. BAPVC's success is attributed to its three pillars of support.

#### Three Pillars

- Industry sets research agenda, assures relevance, provides path to commercial impact, contributes funding
- Universities and National Labs conduct innovative research, provide workforce development
- US Department of Energy provides leadership, support and guidance

The consortium is funded by the U.S. Department of Energy, industry members including GCEP and the participating universities. DOE provided an initial funding of \$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. During the past year, this award was extended by 18 months through December 31, 2017 with the addition of \$2 million funding.

BAPVC provides a vibrant forum for interaction among 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. Our thesis is that great innovation is more likely stimulated by the collective efforts of manufacturing and academic experts working together rather than direction from either community alone. In BAPVC, industry members deliver far more than guidance and advice, they are part of the management team. They review and down select proposals, review projects, and guide the university researchers in setting their research directions.

## **Background**

BAPVC's industry members developed guidance for the next phase of BAPVC research that places much greater emphasis on exploration of technologies that will reduce the CapEx of PV manufacturing. New technologies with very low CapEx and production cost, based on defensible intellectual property created in the U.S., will enable renewed growth of a sustainable and competitive domestic PV manufacturing industry.

Research will focus on the development of PV devices, materials, manufacturing methods, and understanding of reliability that enable disruptively-lower costs and rapid scaling. A reduction in capex has extra leverage toward these goals because it reduces costs, enables cash-flow-positive growth at lower margins, and enables old-technology-capacity to be replaced by new capacity thus accelerating industry progress. High reliability and confidence in the reliability is required to be able to scale a new technology and have that product be financeable at low interest rates. A module which addresses these needs would have the following characteristics as targets:

- Very low CapEx intensity (target  $< \$0.25/W_p$  p.a.)
- High conversion efficiency (target  $> 20\%$ )
- Very low product manufacturing cost ( $< \$0.25/W_p$ )
- Excellent environmental profile
- Long module lifetime ( $> 35$  years) with low degradation (target  $< 0.2\%/year$ )

Achieving these goals requires new structures and approaches relative to current production or in near term development within industry. Pathways to reaching these goals encompass research on both the traditional as well as new material classes that can challenge the dominance of incumbent PV technologies. Industrial R&D, in the face of decreasing profit margins, is constrained by a 5-year development horizon to incremental improvements of the incumbent technology. BAPVC's industry members bring industrial expertise to the consortium to increase academic researcher's understanding of manufacturability. Guidance from industry assists BAPVC to identify avenues of investigation just beyond industry's own mission critical research while avoiding technologies that have been tested and discarded in the course of proprietary industrial research. BAPVC established a strong community that has bridged these two groups and created a working platform that enables truly disruptive research – performed in the leading academic and National laboratories, under the guidance of US PV companies.

BAPVC projects have aggressive goals set to develop disruptive technologies. Such projects frequently present multi-faceted challenges needing collaborative, consortium-sized efforts to advance to the next technology readiness level. BAPVC brings together materials scientists, device engineers, manufacturing specialists and equipment suppliers to capture the revolutionary advantage of our technologies.

## **Results**

Using the added resources provided by DOE and industry members, BAPVC launched a Request for Proposals (RFP) to solicit new projects addressing the vision of the Industry Board. Part of this guidance encouraged a shift in operations from research teams loosely coordinated in thrust area structure to increased cohesiveness delivered in jointly funded, multi-investigator research teams. Through this competition, BAPVC selected six new teams for projects. These

will support 23 investigators from 13 universities and 2 national laboratories. The new projects are as follows:

“Economic silicon heterojunction solar cells with optimized photon management”

Harry Atwater (Caltech), Stuart Bowden (ASU), Mark Brongersma (Stanford), and Tonio Buonassisi (MIT)

“Innovating module materials and metrologies for reliability of BAPVC technologies”

Reinhold Dauskardt (Stanford), Jeffery Urban (LBNL), Alberto Salleo (Stanford), Sue Carter (UC Santa Cruz), and Mathew Reese (NREL)

“Low-cost, high efficiency 1.7 eV MgCdTe DH subcells for Si based tandems”

Yon Hong Zhang (ASU), Mike Scarpulla (Utah), and Chris Ferekides (USF)

“Low capex solar manufacturing enabled by perovskite semiconductors”

Mike McGehee (Stanford), Paul McIntyre (Stanford), Zachary Holman (ASU)

“Wafer level processing of silicon substrates to improve their material quality and extend ingot yield for very high efficiency solar cells”

Ajeet Rohatgi (GIT), Bhushan Sopori, Teh Tan, and Mike Stavola (Lehigh)

“Network modeling for rapid optimization of lifetime, efficiency and capex of PERC solar cells”

Roger French (CWRU), Timothy Peshek (CWRU), Hongping Zhao (CWRU), and Bryan Huey (UConn)

These new projects will join the ongoing work of the Co-Directors. Cui’s group at Stanford University aims to generate high efficiency ultrathin silicon solar cells with an understanding of their device physics and developing manufacturing process. They have reported progress in the production of  $<10\ \mu\text{m}$  monocrystalline silicon at a wafer scale with regular fabrication processability. They have experimentally demonstrated that with novel nanoscale photon management structures, where a  $3\ \mu\text{m}$ -thick Si can absorb 58% of the above bandgap sunlight and  $7\ \mu\text{m}$ -thick can absorb 86%. They studied the balance between excellent photon absorption and efficient electrical collection in ultrathin monocrystalline-Si solar cells, and demonstrated  $>80\%$  EQEs at wavelengths from 400 to 800 nm in a sub- $10\ \mu\text{m}$ -thick Si solar cell, resulting in 13.7% power conversion efficiency. Furthermore, a thin Si manufacturing technique is explored with metal-assisted chemical etching (MACE), and the fundamental mechanisms of the etching process have been clarified.

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- $2\ \mu\text{m}$  by KOH chemical etching (see Fig. 1(a,b)). These ultrathin Si wafers exhibit excellent mechanical flexibility and bendability, as shown in Fig. 1(d,e). Unexpectedly, these ultrathin Si materials can be cut with scissors like a piece of paper, and they are robust during various regular fabrication processing. To demonstrate their processability, 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. Light absorption in 3  $\mu\text{m}$  thick Si film is largely enhanced with a 130% increase in  $J_{sc}$ , achieving 58% absorption of the above bandgap sunlight. The 7  $\mu\text{m}$  thick Si can absorb 86% of the above bandgap sunlight.

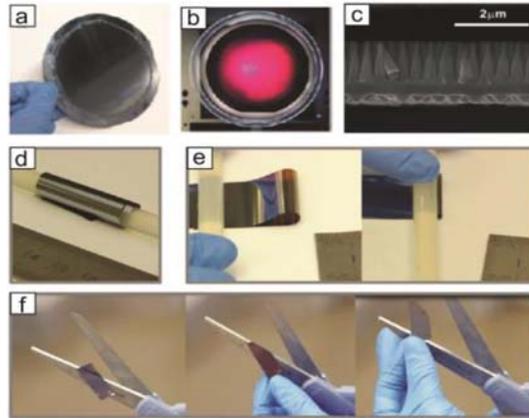


Figure 1. (a) and (b) 4-in. wafer-size ultrathin Si films illuminated by the white light from the backside. (c) SEM image of the cross sections of a double-sided patterned films. (d) A 3  $\mu\text{m}$  thick Si film was wrapped around a plastic rod with diameter of 7 mm. (e) The Si film was folded and then pressed by the plastic rod. The minimum folding radius is around 1 mm. (f) Si cutting process using scissors. Ref. [1]

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- $\mu\text{m}$ -thick Si solar cell with a 13.7% power conversion efficiency which utilizes an 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 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-back contact design and the nanocones. Its all-back-contact design prevented Auger recombination loss near the front (see Fig.2), and its nanocone structure minimized the increase in surface area while enhancing the light absorption significantly.

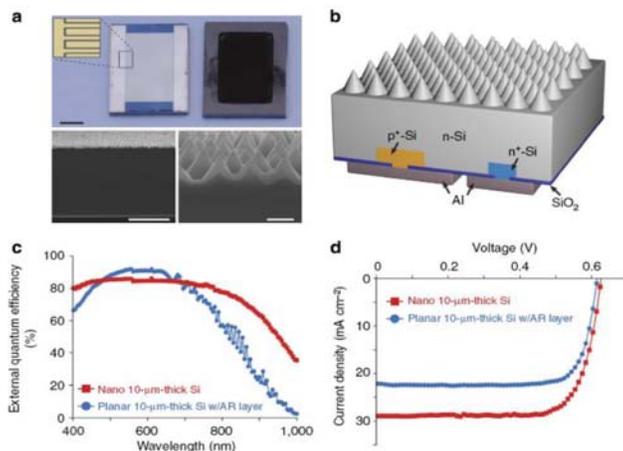


Figure 2. Ultra-thin Si nanocone solar cell. (a) Optical image and SEM cross-sectional views of the 10- $\mu\text{m}$ -thick Si solar cell. (b) Schematic illustration of the device. (c) EQE data of the device and a planar control. (d) J–V characteristics of two devices in c. Ref. [2]

Finally, MACE is explored as a method of scalable production for thin Si because it is an easily scalable, low-cost selective wet etching technique. The final goal is to simultaneously etch thin Si wafers of arbitrary thickness directly from an ingot with little raw Si material loss. Thus far, the Cui group has demonstrated slicing vertically through a wafer of over 300  $\mu\text{m}$  thick to produce long silicon slivers, as shown in Fig.3. To facilitate this goal, the fundamental mechanisms of the etching process were studied and clarified (Ref. [4]). Upon noticing that some of the etched Si looked very dark to the eye, the group further explored and developed a hybrid metal-semiconductor nanostructured interface, producing a structure that absorbs an average 97% of the visible spectrum with a sheet resistance of 16  $\Omega/\square$  while 60% of the top-down surface is covered with metal. An example false-color SEM of such a structure is shown in Fig. 3(f). The group continues to explore the applications of ultra high-aspect ratio MACE and this nanostructured interface, attempting to integrate it into a fully functioning Si solar cell.

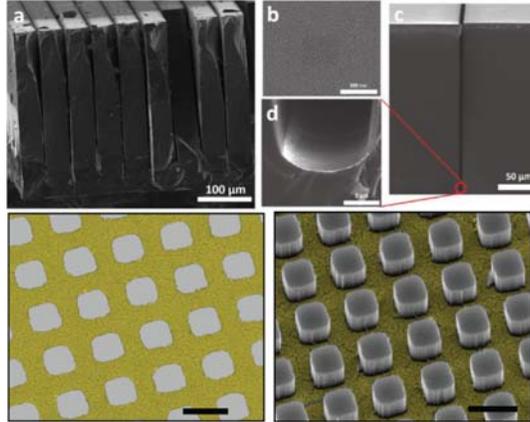


Figure 3. Metal-assisted chemical etching of Si. (a) SEM cross section of 5  $\mu\text{m}$  wide lines etching over 300  $\mu\text{m}$  down. (b) Nanostructure of evaporated metal layer. (c) MACE trench. (d) Zoomed in bottom of trench. (e) False-color SEM of pre-etched metal-patterned Si. (f) Post-etched pillar nanostructured Si. Scale bar is 500 nm for (e) and (f). Ref. [3] + [4]

Future work focuses on the push for higher efficiencies in the 10-20  $\mu\text{m}$  Si solar cell. This goal can be accomplished via two methods: 1) producing a nanostructured heterostructure intrinsic thin-layer (HIT) solar cell; 2) good passivation with an oxide layer and careful surface preparation of ultrathin Si solar cells. The goal is to improve the 13.7% efficiency to 17.5%, and then further to over 20%. 3) Develop scalable and low-cost manufacturable process to generate thin Si with low material loss.

In work at Berkeley, Javey's group pursues two main research directions were pursued under their BAPVC project title: 1. Simple InP solar cells based on low-cost vapor-liquid-solid (VLS) growth; and 2. alternative contacting strategies for high efficiency c-Si solar cells.

#### **InP VLS cells**

The VLS process allows the growth of large grain InP thin films on low-cost substrates with optoelectronic properties approaching those of epitaxial grown layers, enabling the fabrication of low cost InP thin-film solar cells with efficiencies >12%.

#### **Dopant-free contacts for c-Si solar cells**

Commercially available silicon solar cells utilize doped silicon layers to collect electrons and holes - an approach which is hindered by a number of optoelectronic losses. This project involves the trial an integration of other materials, for example metal oxides and alkali metal salts, as a substitute for the doped silicon layers – which do not incur the same losses.

In the realm of thin-film InP PV, the group has developed further methods for improving dopant profiles and microscale localized process control, implementing methods for in-situ doping of thin-films via phosphorization with spin-on diffusants as part of the required cap structure. The method demonstrates control over doping on the micron scale, through the growth of single crystal domains in close proximity that display high concentrations of both holes and electrons. (Figure 4). The optoelectronic quality of the material grown with in-situ doping via this method is comparable to single crystal wafers, and the material can be grown easily on an amorphous substrate with a nucleation layer or on metal substrates for direct cell contacts.

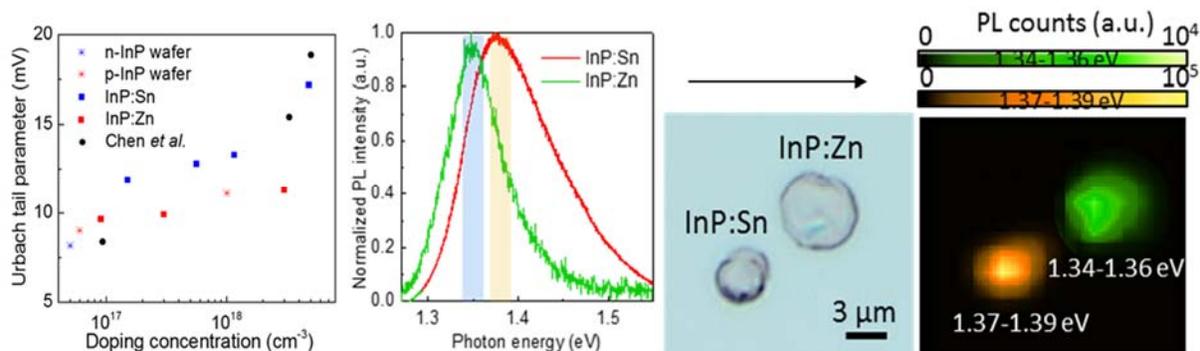


Figure 4. Demonstration of co-doping with a single growth run, via PL mapping and a Burstein-Moss shift. Urbach tail parameter of p- and n-type material with varied doping concentration, close to wafer values.

Under the research topic of alternative carrier-selective contacts for c-Si solar cells, a number of advances were made within 2016. Firstly, a low work function LiF based electron contact was developed to compliment the group's existing high work function MoO<sub>x</sub> based hole contact (See Figure 5). These advancements led to the development of high efficiency dopant free asymmetric heterocontact (DASH) silicon solar cells with efficiencies close to 20% - the first of their kind to demonstrate competitiveness with conventional processes<sup>5</sup>. This low resistivity LiF based contact also allowed the fabrication a novel n-type partial rear contact cell (with an efficiency above 20%) without the need for localized phosphorus doping.

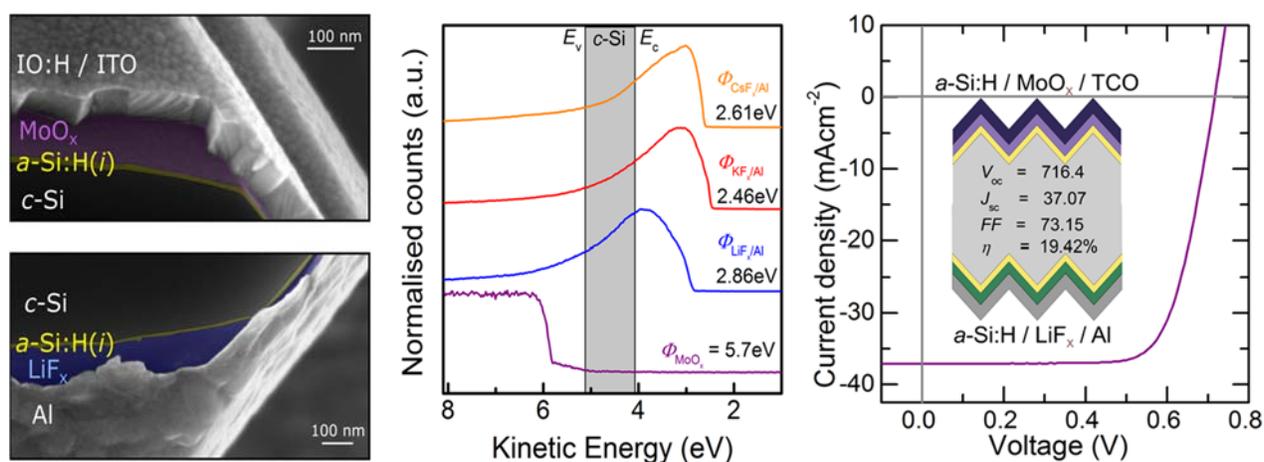


Figure 5. Cross section, contact work function measurements and *JV* curve of the DASH solar cell.

For further advances in high efficiency InP thin-film solar cells, the group will focus efforts on leveraging doping and process control methods required to fabricate more advanced structures on higher quality n-body films, that can obtain high theoretical  $V_{oc}$ .

As for selective-contact development, future research will focus on advancing towards a higher efficiency second generation DASH cell structure whilst simultaneously investigating the thermal and humidity stability of selective-contact candidates.

## References

1. S. Wang, B. Weil, Y. Li, K. X. Wang, E. Garnett, S. Fan, and Y. Cui, "Large-Area Free-Standing Ultrathin Single-Crystal Silicon as Processable Materials," *Nano Letters* 13(4393) (2013).
2. S. Jeong, M. D. McGehee, and Y. Cui, "All-back-contact ultra-thin silicon nanocone solar cells with 13.7% power conversion efficiency," *Nature Communications* 4(2950) (2013).
3. V. Narasimhan, T. M. Hymel, R. A. Lai, and Y. Cui, "A hybrid metal-semiconductor nanostructure for ultrahigh optical absorption and low electrical resistance at optoelectronic interfaces," *ACS Nano* 9 (11) (2015)
4. R. A. Lai, T. M. Hymel, V. Narasimhan, and Y. Cui, "Schottky Barrier Catalysis Mechanism in Metal-Assisted Chemical Etching of Silicon," *ACS Applied Materials & Interfaces* 8(14) (2016)
5. J. Bullock, M. Hettick, J. Geissbühler, A. J. Ong, T. Allen, C. M. Sutter-Fella, T. Chen, H. Ota, E. W. Schaler, S. De Wolf, C. Ballif, A. Cuevas, A. Javey, "Efficient silicon solar cells with dopant-free asymmetric heterocontacts", *Nature Energy*, 15031, 2016.

## Contacts

John P. Benner, Executive Director BAPVC, [jpbenner@stanford.edu](mailto:jpbenner@stanford.edu)