DOE Workshop on Silicon Photovoltaics
July 29, 2015

Introduction

The purpose of this workshop
The Department of Energy Solar Energy Technologies Office held a workshop on Silicon Photovoltaics Research Directions for Beyond the SunShot Initiative on July 29, 2015 in Keystone, CO in conjunction with the NREL Workshop on Crystalline Silicon Solar Cells and Modules. The Department of Energy SunShot Initiative aims to bring installed photovoltaic systems price down to $1/W by 2020. The purpose of this workshop was to discuss and survey the impactful research directions for silicon based photovoltiacs beyond the 2020 goal.

Workshop participants
The workshop was attended by over 70 participants with representation from universities, national laboratories, international institutions and industry. The breakdown of participant affiliation is shown in Figure 1. The representation of participant area of expertise is shown in Figure 2.

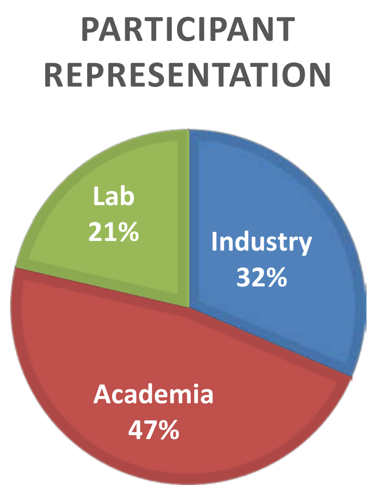

Figure 1. Breakdown of workshop attendees by affiliated institution type.

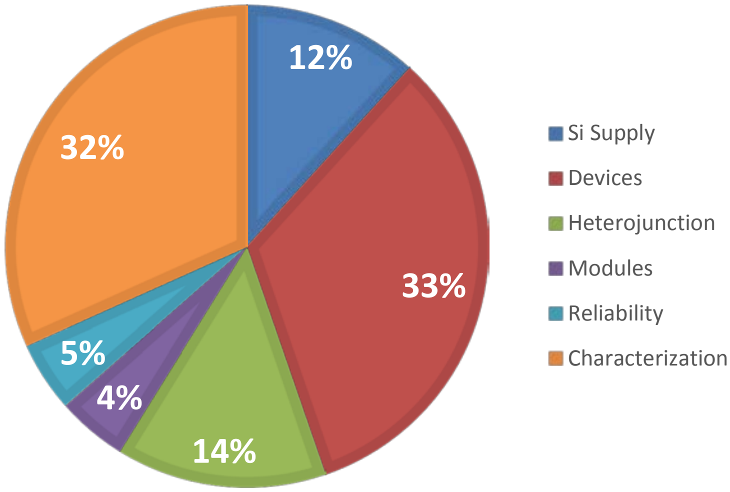

Figure 2. Breakdown of workshop attendees by area(s) of expertise

Participants were asked to separate into breakout groups by research areas. These were: Metrology and Characterization, Cell Processing and Metallization, Heterojunctions, Silicon Supply, and Modules and Reliability. Each group discussed the following questions with consideration to their particular area.

Summary of opening remarks and discussion questions

The SunShot Initiative aims to bring the price of installed solar energy to $1/W or $0.06/kWhr at the utility scale, which would move the technology to a competitive level with traditional electricity generation sources. The breakdown of funding as of 2015 dedicated towards technology and topic areas as managed under the Photovoltaics subteam of the SunShot Initiative in support of this goal is shown in Figure 3.

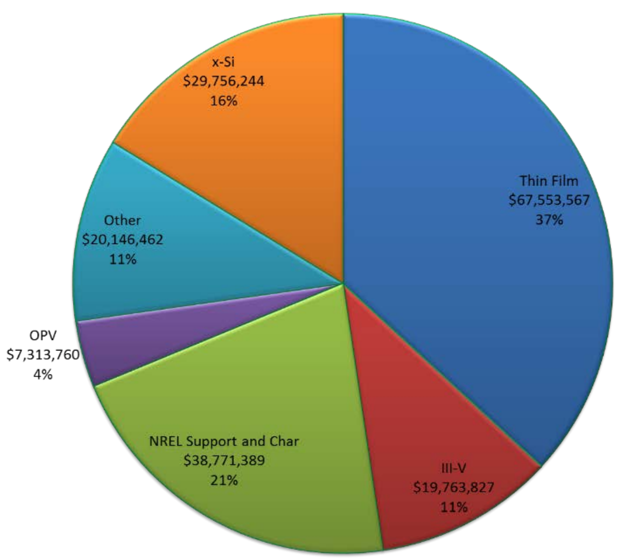

Figure 3 Breakdown of topic area funding in the Photovoltaics subteam under the SunShot Initiative as of July 2015

Silicon based photovoltaics represent the majority of the photovoltaics market and has been so historically. While prices of silicon based photovoltaics have fluctuated due to supply chain availability and cost, it has maintained its dominance of the industry with more than 60 GW of manufacturing capacity worldwide and more than 200 GW cumulative installed capacity.

While it is often now assumed that silicon will continue to be the dominant driver of the industry, this has not always been the case. In the 1990s and early 2000s, silicon based photovoltaics was costly and much effort was spent in developing alternative absorber technologies such as thin film PV and organic PV. The question now is: what is needed for silicon based photovoltaics to continue to be a major contributor to driving down the costs and price of solar energy? Since it currently represents more than 90% of the industry, is it sufficient for the industry to improve the technology incrementally or is a paradigm shift needed? What are the major opportunities and barriers in silicon photovoltaics technology that would benefit from investigation in order to accelerate cost reductions?

Summary of breakout group reports

Overview

With respect to the first question about whether silicon photovoltaics would be able to reach prices beyond the SunShot goal through incremental improvement or if a step-function development was necessary, the major sentiment was that silicon photovoltaics would be able to reach further module cost reductions through incremental improvements rather than a radical change. Examples given of what would be considered incremental improvements included:

- integration of techniques currently being researched on passivated contacts and interdigitated back contacts by manufacturing. If there was an improvement that was slightly more aggressive, there was a sentiment that there could be a transition to thin wafers or direct wafer
- upstream reduction of defects, such as oxygen and metallic impurities, in silicon ingots and wafers
- accelerating the speed in cycles of learning through faster and standardized metrology techniques that can be incorporated in-line
- increasing throughput
- increasing durability and reliability of modules

While it was generally agreed that incremental improvements would be sufficient, several groups noted that there were radical improvements that would be beneficial to research for aggressive price reductions by 2030. These mainly focused on reducing the amount of the material in the process through methods such as:

- kerfless or direct wafers
- alternatives to silver for metallization

There were also suggestions with respect to program development. Two groups, the Characterization and the Silicon Supply groups, suggested that providing the opportunity to propose and run smaller, shorter research projects that were focused on examining an industrially impactful issue would be beneficial in terms of having improved flexibility in research directions and a more focused research project aimed at finding solutions to a well defined research problem.

Metrology and Characterization

There were two breakout groups that were focused on metrology and characterization issues for silicon photovoltaics along the full line of the process from the ingot to the final module. Below is a summary of the impactful areas of research that were discussed by both groups:

- Faster and more sensitive methods to detect, track in-line and mitigate of oxygen and iron related defects should be developed for monocrystalline silicon wafers.
- Kerfless, direct and epitaxially grown silicon 'wafers' should be developed through reduction of defects during growth and through demonstration of substrate reuse.
- Metrology practices should be standardized so that useful comparison can be made between measurements of different material sources and devices.
- Develop equipment and processes to predict possible device failures in the upstream phases of wafer and cell fabrication

The teams felt that collaboration with industry was an important component for guiding and developing the field.

Silicon Material

This group focused on the polysilicon, ingot and wafer supply side of silicon photovoltaics. Below is a summary of the impactful areas of research discussed by this group:

- The group felt that incremental developments in industry will be enough for silicon solar cells to reach 3 cents/kWhr in 15 years. This would be accomplished through larger ingots and wafers, finer defect control, innovations in crucible coating, reduction of consumables, reduction or recycling of kerf and developments of crystal growth techniques.
- The innovative breakthroughs in the silicon supply area would be related to the development of kerfless wafers and direct wafering techniques.

Cell Processing and Metallization

This team looked at the area of silicon cell processing and fabrication through the metallization step. Like the silicon materials groups, the cell processing team also expressed the belief that incremental developments in the silicon cell industry would lead to 3 cents/kWh in 15 years. The metrics by which improvements in this area could be measured would be the resulting cell performance and cost, industrial impact, and the scale-up potential of the technology.

The main areas of beneficial research discussed by this group were:

- Wafers would need to be thinner, lower cost and of high quality. An area that would benefit from development is the pre-processing and gettering step.

- The diffusion step would need to examine the areas where costs could be lowered. Some examples given include abatement, cleaning, increasing throughput such as performing double sided diffusion in one step. The group also brought up the possibility of streamlining the diffusion step, the future of back surface field formation and the development of ion implantation.
- Plasma enhanced chemical vapor deposition (PECVD) was identified as an area that could benefit from developments to move towards deposition at atmospheric pressures, increased throughput (which may be aided by moving to atmospheric deposition processes), reduced abatement and cleaning costs
- Light trapping and integration of light trapping into cell designs and fabrication.
- The use of Ag in metallization should be reduced or replaced with an alternative metal. Grid designs should be optimized to the cell architecture. Interconnection designs between cells could also be improved.

Heterostructure cells

There is currently much interest and research effort in the area of heterostructure solar cells, not only in the context of a "Heterojunction with Intrinsic Thin layer (HIT)" cell design by Sanyo now Panasonic, but in the context of heterointerfaces of various materials with silicon for passivated contacts or contacts for improved cell performance beyond the aluminum back surface field cell design. The group dedicated to discussing this area identified the main metrics by which to measure progress in this research topic as the balance between the efficiency of the cell that employs heterostructures and the cost of such a fabrication process considering the number of steps required to employ the process. These areas are also the main areas that would benefit from research:

- Simple and low cost processing methods for producing heterostructure cells would need to be developed
- Heterostructure cells often employ and benefit from a crystalline wafer that is thinner than standard solar grade wafer as carrier collection is more dependent on diffusion. Developing methods to handle thin wafers while maintaining throughput and yield would be important in this case.
- There were some special considerations for interdigitated back contact solar cells and carrier selective contact designs. These structures require patterning which would increase the processing complexity and cost, both of which would need to be addressed. It would be useful to conduct a survey of materials that might be applicable for heterostructures, beyond those that have been well studied for silicon passivation.
- Some iterations of heterostructure cells may have applications in bifacial modules and standards would need to be developed for such modules.
- The reliability of these new interface combinations and cell structures would need to prove reliable.
- In these cells, the wafer quality plays an important role so it would be useful to develop an understanding the effect of the wafer properties on cell properties.

Modules and Reliability

Ultimately, solar cells are deployed in the form of modules in the field. This group discussed the research areas that would improve module performance and reliability:

- The materials in modules should be engineered to have increased durability.
- Module structures should be designed to have ease of assembly, installation, connection and communication.
- Module power out can decrease when heated which could be mitigated by temperature management methods.
- Smart electronics that monitor module outputs such as SunsVoc, performance, and field yield would provide important data needed to evaluate the reliability of modules in the field.
- Understanding the effect of soiling on module reliability was an important issue that was brought up for silicon modules.
- Overall for reliability, projects to understand the physics of failure, implications of geographical location of the module to resulting performance and performance over module lifetime would be beneficial. The development of standards for reliability testing and innovating technology to test and collect data on modules would also help in developing an improved understanding of reliability.

Summary Observations and Next Steps

The workshop attendants discussed the major areas of focus for silicon modules to reach 3 cents/kWh by 2030. Some key themes that emerged were:

- Several groups felt that the silicon module industry could reach 3 cents/kWh through incremental improvements to the current cell structures.
- There was interest in understanding the effect of quality of the upstream silicon ingot and wafer on the resulting cell.
- There was a general trend in group report outs to reducing materials usage in module fabrication, such as increasing silicon usage efficiency and reducing cell thickness.
- Incorporating cost-benefit analysis when developing technologies and increased collaboration with industrial partners would be useful to outline the potential of a technology.

The information from this workshop has been and will continue to be used to inform program development for programs under the SunShot Initiative. As this major industry continues to develop, often changing rapidly, the SunShot Initiative will continue to solicit feedback from the silicon photovoltaics community through workshops, web based requests for information, and discussion to build a temporal understanding of research trends and industrial needs.

DOE Si workshop summary

29 July 2015

Overall Themes

- Incremental/Evolutionary will reach 3 cents/kWh in 15 years
- O, defect reduction, mapping and tracking
- Faster cycles of learning
- Kerfless, direct wafers
- Reliability
- Process integration, higher throughput
- Standardization
- Smaller, focused, industrially guided projects

Overall Metrics

- LCOE
- Efficiency
- Cost
  - Cost modeling, cost benefit analysis
- Reliability

Metrology

- P-type mono: BO complexes
- N-type mono: O precipitates
  - Detecting and resolving O precipitates
  - Fe detection
- p-type multi: kerfless, epi, direct wafer. Need to solve reuse, crystal defects (stacking faults) and metal impurities
- n-type multi: O detection methods that are faster and down to 10^{10} cm^{-3} limit.

Metrology

- O detection and tracking
  - Tracking gettering and hydrogen passivation effects
- Defect tracking
  - In-line, feedback, faster learning cycles, binning, impact on reliability, at ingot level
- Develop process equipment with built in metrology
- Proactive: predict failure upstream
- Tools: PL, PC, FTIR, RUV
- Standardization: to be able to compare measurements

Metrology

- Types of projects
  - More projects at smaller $/project
  - Focused, less partners
  - Guided by industry
- Metrics:
  - LCOE
  - EL barcoding to track wafers
  - Collaboration with industry

Si Material

- Incremental will reach 3 cents/kWh in 15 years
  - Reduce consumables
  - Larger ingots, wafers
  - Defect control
  - Crucible coatings, reuse, elimination
  - Thorough analysis of crystal growth techniques
  - Recycling kerf

Si Material

- Innovations
  - Kerfless, direct wafering
- Projects
  - Need to incorporate cost benefit analysis
  - Small projects suitable for universities and labs

Cell Processing and Metallization

- Incremental will get to 3 cents/kWh in 15 years
- Major areas:
  - Wafer: cheap/high quality, thinner (20 um), purity, mc-Si vs Cz, pre-processing and gettering as a challenge (always an extra step)
  - Diffusions: costs (abatement, cleaning, throughput, two-sided), streamlining, future of BSF, implantation
  - PECVD: atmospheric, higher throughput, spray-on, reduced abatement costs, reduced cleaning costs, multipurpose layers
  - Metallization: Ag (reduce or alternative), optimized grid design and interconnection

Cell Processing and Metallization

- Other
  - Light trapping, integration
- Metrics
  - Cell performance, cost analysis, publications, industrial impact, scalability

Heterostructures

- Need cheap and simple processing
- Thin wafers – how to handle?
- IBC and CSC:
  - How to reduce patterning and processing cost
  - Need wider materials search (beyond SiO_2, SiNx, Al_2O_3, a-Si:H)
  - Light management
  - Standards for bifacial
  - Could investigate tandems but need 20% cheap top cell
- Reliability

Heterostructures

- Metrics
  - Efficiency
    - Transparency, lifetime, contact resistance for CSC
    - Increased energy harvest due to CSC such as lower TC, higher LLE, higher off-axis light capture
    - Understand loss mechanisms and efficiency limits
  - Cost: wafer thickness, # of steps, Ag usage, wafer quality, uniformity, degradation rate

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Modules and Reliability

- Lowering costs
  - understand physics of failure
  - lifetime prediction
  - geographical implications
  - standards: develop common method, innovative design, physics based testing, module integrated electronics