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Eighth Workshop on Crystalline Silicon Solar Cell Materials and Processes

Summary Discussion Sessions

D. Swanson, R. Sinton, M. Stavola, T. Tan, and B. Sopori
National Renewable Energy Laboratory

Workshop Chairman: B. Sopori

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Executive Summary

The 8th workshop was attended by 114 scientists and technologists in the photovoltaic (PV) and microelectronics fields, making it the best-attended workshop to date. The popularity of the workshop stems from its scientific content, which emphasizes the fundamental aspects of science relevant to the industry problems, and the organizational format, which emphasizes discussions. With its updated title and theme matching the issues at hand, the workshop appears to be particularly satisfying to industry.

This year the title of the workshop was changed to the "8th Workshop on Crystalline Silicon Solar Cell Materials and Processes," aimed at emphasizing the increasing need to apply defect-engineering concepts in solar cell processing. The salient points that emerged in various discussion sessions are:

1. The poly feedstock availability/shortage is an important issue for PV companies. The shortage of poly is somewhat alleviated in the last year because of a drop-off in the microelectronic industry. The attendees felt that the issue is primarily business oriented. A number of approaches are being pursued to develop technology for making "solar-grade poly" at a cost affordable to the PV industry. At the same time, there is an increasing attempt to lower the use of silicon by going to thinner wafers (which also usually yield higher cell efficiencies).

2. Commercial Si solar cell efficiencies are primarily limited by defect clusters. It was shown that defect clusters promote impurity precipitation during the crystal growth that are difficult to getter or passivate during cell processing. Hence, aside from cleaning up the crystal growth process itself, a major emphasis of the Si program must be placed on developing post-growth processes that can getter precipitated impurities in reasonable processing times. Analyses suggest that the current materials can yield about 18% commercial cell efficiency if this problem can be adequately addressed.

3. A great deal of understanding of the hydrogen diffusion and passivation has been gained in last few years. However, mechanisms involved in hydrogen passivation of transition metals remain quite vague.

4. Experimental results from production suggest that it is more favorable to use controlled poly of higher quality than a lower-cost, lower-grade material. The former results in higher yields, and hence is more cost effective.

5. PV industry needs automation and process control to lower the product cost. Almost every company has embarked on such a program. Unfortunately, many control techniques are not well defined.

6. Thin-film Silicon solar cells are part of a future technology that seems to offer a strong promise of low cost and high efficiency.

Session 1. Feedstock Issues and Wafer Supply

Panel Discussion: *Pathways to Overcome Feedstock Problem*

Discussion Leader: Chandra Khattak

Panel: Jan Maurits, Simon Tsuo, Dimitri Strebkov, Ted Ciszek, Tim Bruton, Josef Szlufcik, Kim Mitchell

In the past, the silicon PV industry has enjoyed a situation of using microelectronic rejects such as tops and tails, pot-scraps, and off-spec material as the feedstock for silicon ingots. While the supply from these sources is shrinking, the demand for the feedstock is growing because of the increased PV production. This situation has led to an increase in the cost of feedstock and created questions about its availability for the future growth of PV. There are two approaches to mitigating the feedstock issue. One is to maintain a steady supply of feedstock by creating a dedicated source for the PV industry in a manner similar to that for the microelectronic industry, which will wean the PV industry from the microelectronic industry. This approach does require a sizeable initial investment and introduces an uncertainty, because the quality of such a feedstock is not defined. The other approach to lowering risk of a feedstock shortage is to reduce the use of Si material.

The subject of Si feedstock for photovoltaics is primarily a business issue, with the objective of controlling the feedstock cost below an acceptable value (typically $25/kg). This acceptable cost of the feedstock may change, as evidenced by the fact that just a few years ago the same limit was $10. The current PV production exceeding 125 MW/year requires more than 200 MT of feedstock material. The present supply of cheap IC scrap has become highly unreliable; hence, a dedicated solar-grade Si feedstock must be available. This issue is now being addressed in several countries. For example, the silane decomposition processes, using either hot-filament or plasma, are under development both in the United States (AsiMI) and in Russia; they appear to be able to meet the $25/kg goal. These silane processes offer an advantage of producing high-purity Si with a high yield as compared to the tricholoro-silane-based process. Other potentially low-cost processes are also under evaluation. For instance, NREL is evaluating a process of purifying the metallurgical-grade Si in the liquid state, and Britain is evaluating the epi-on-metallergical-grade-Si cell fabrication process.

Improved solar cell design and processing can significantly contribute toward alleviating the Si feedstock shortage. With lower kerf in wafering, thinner wafers and higher cell efficiencies are possible. This requires automation to get high mechanical yield and advanced gettering processes for achieving high-efficiency cells.

It appears difficult to define solar-grade Si, for it seems to depend upon the cell-efficiency requirement and the cell fabrication processes involved. ASiMI has a preliminary spec on the impurity contents of its solar-grade Si: B<20 ppb, P~4 ppb, C~1 ppm, O~5 ppm, Fe~20 ppb; but this appears to be specific to AsiMI's high-purity silane process only.

Session 3. Material Issues: Defects and Impurities, Impurity Gettering

Open Discussion: *Control of Impurities/Defects and Impurity Gettering*

Coordinator: James Gee

Understanding gettering mechanisms and optimization of gettering have been quite instrumental in fabrication of ~15%-efficiency cells on low-cost, single-crystal and mc-Si. Al and P gettering typically lead to an increase in the minority-carrier lifetime from an initial value of 5–10 μs to 30–50 μs at the end of the process. But, the same processes may not be sufficient to raise the cell efficiencies toward 18%; some processing adjustment and additional steps are necessary. While the manufacturers prefer simple approaches, a compromise should be made between the process complexity and the cell efficiency.

In mc-Si, metal precipitates have been found in defect-cluster regions where the carrier lifetime is difficult to improve by a typical gettering treatment (e.g., using P or Al at 850 °C for 0.5 h). It is now understood, at least in principle, that gettering of precipitated metals may be difficult, and the gettering process may even degrade the lifetime before improving it. Based on these understandings, more effective gettering procedures may be designed. Surface "bad region" can lead to excess leakage, but it may be prevented by gettering of the surface region. On a philosophical basis, gettering should be viewed as a final cleaning tool rather than a cure-all process step. Thus, the first approach to deal with heavily contaminated materials, e.g., the electromagnetic casting material, should be to clean up the crystal growth process itself.

The PV industry needs simple tools for diagnosis and process control. However, such tools are not available at this time. The problems in using simple monitoring tools are further discussed in the Discussion Session 4.

Panel Discussion: *Future Trends in Si Material Technology that Can Meet the Anticipated Production Volumes in a Cost-Effective Manner*

Discussion Leader: Mike Kardauskas

Panel: Dan Meier, Tadashi Saitoh, Santo Martinuzzi, Terry Jester

ASE Americas is developing a new EFG process aimed at reducing Si consumption and improving throughput. The process consists of growing a rotating (>60 rpm) tubular ribbon (75 um thick). The tubular ribbon crystal will be laser cut into 2000-mm x 1570-mm wafers. This technique is expected to be in production some time after the year 2000. The cost distribution, at a 50 MW/year production level, is expected to be: 27% for wafers, 33% for cell fabrication, and 33% for module fabrication.

Siemens is aiming at producing larger (6-in) diameter wafers. It is expected that the wafer thickness will initially be reduced to 250-μm and then to 150-μm. Although achieving

150 μm thick cells is currently possible, it seems to suffer from heavy mechanical losses in wafering and etching steps. Automation will be incorporated to alleviate these problems.

Japan is planning on making a heavy investment to expand production capacity. The cost reductions are expected by making flat-bed crystal growth, processing thinner cells to reduce Si consumption, and targeting higher-efficiency cells and modules. Low-cost, thinner, plastic module structures are being proposed.

Europe is planning to address cost issues by using metallurgical-grade Si as the low-cost feedstock, and lowering the defect densities in cast ingots through a reduced cooling rate during crystal growth. Furthermore, thinner and textured wafers, impurity gettering, and hydrogen passivation will be included in cell processing.

Session 4. Advanced Diagnostics

Panel Discussion: *Process Monitoring and Automation for PV-Si Industry*

Discussion Leader: Ron Sinton

Panel: Jerry Culik, Ajeet Rohatgi, Arne Matthäus, Martha Symko-Davies

To a large extent, the PV industry uses little in-line process monitoring. The workhorse tool in the industry is the final solar-cell, I-V curve. The requirements for process monitoring and diagnostics were discussed from two viewpoints. A complete scientifically decisive set of tools was described. Somewhat in contrast, industry desires a simplified set of tools that in general would be nondestructive, have no impact on throughput, have low cost, and would give quick decisive results of a go/no-go kind.

Specific problems in process control were discussed, including: (i) lifetime at the ingot level, (ii) lifetime at the wafer level for various states of processed wafers, (iii) optical parameters, (iv) mechanical wafer parameters and dimensions, (v) sheet resistance control, (vi) screen-print parameters and contact resistance, and (vii) tab pull strength. There are many open challenges in this area for future workshops. The technical expertise seems to exist, but needs to be creatively applied to the specific requirements of the industrial production line.

The oral presentations, preceding the panel discussion, discussed in detail three techniques for lifetime measurement. A general unifying theme for all techniques was the importance of minority-carrier injection level for understanding lifetime data. Using the quasi-steady-state photoconductance technique, data covering several orders of magnitude can be analyzed in terms of a calibrated minority-injection level. For some samples, the very low injection region shows trapping effects, the mid-injection levels (up to that approaching the doping level) indicates the expected SRH behavior, and for high injection levels (near and above the doping level) the doped surface emitter-saturation-current density can be characterized. Possibilities for misinterpreting data were discussed: trapping at very low injection levels can mimic high lifetime, and the use of transient photoconductance decay (PCD) on inhomogeneous regions will overestimate the average lifetime by giving a result characteristic of the best portion of the area.

The quasi-steady-state photoconductance measurement gives an area-averaged lifetime result. In contrast, the microwave PCD and the surface photovoltage (SPV) can give high-resolution mapping. The SPV technique is performed at low injection level, while the microwave PCD is at a high injection level. The two results can be complementary. Both techniques are being applied to detect and map contamination caused by Fe and other elements. Examples of the evolution of the lifetime response with repeated laser illumination were presented from the PCD tool. A high-resolution map from a Solarex ingot was shown indicating the apparent profile for dissolved Fe.

The fundamentals of the SPV technique were explained in detail. Applications include the detection and discrimination of Fe and Cu. Fast, high-resolution mapping requires data correction to account for the limited frequency response of the wafer SPV signal.

Session 5. Solar Cell Processing

Chairs: Isabelle Perichaud and George Rozgonyi

Presenters: Peter Fath, Tim Bruton, Josef Szlufcik, Armin Aberle, Arun Madan, Parag Doshi, Roland Schindler, Jean-Claude Muller

A formal discussion session for solar cell processing was replaced by a session that included eight review presentations covering a variety of topics: texturing of multicrystalline wafers, advanced emitter and metallization technologies, physics and technology for PECVD nitrides, and RTP techniques for solar cells.

The complexity of a complete optimization for texturing technology was shown. Interactions between diffusion lengths, texture geometries, encapsulation, and cell designs must be considered by simulation to assess possibilities accurately. Different texturing techniques were compared and contrasted. Mechanical texturing appeared to be promising; the estimated cost would be less than US$0.05 per wafer.

Advanced emitter/metallization designs were discussed. Laser-grooving was noted to have exceptionally low cost. The high-efficiency designs using laser-grooving have very high system-operating efficiencies in actual field performance, and enable a technology capable of applications for flat-plate modules as well as concentrator modules up to 40X. The state of the art in screen-printed technologies has also advanced. Several new concepts and results were presented. A design incorporating auto-doping from selectively-screened paste, and PECVD nitride for antireflection and bulk/surface passivation, is especially promising. This process is comparable to the standard homogeneous-emitter process, and has yielded 100-cm^2 cells with efficiencies of 16% on multicrystalline and 18% on CZ material.

The understanding of the science and technology for PECVD nitrides is rapidly advancing. The similarities and differences for three deposition techniques were presented. High-frequency direct-plasma deposition and remote-plasma deposition both result in nominally identical films, once the deposition conditions for each are optimized. Index of refraction is a measurable parameter perfectly correlated with the degree of passivation produced by these films. Low-frequency, direct-plasma deposition results in a poor passivation due to the surface damage caused by the plasma. A detailed study correlates these properties with the specific defect levels. Of particular interest was the description of "K^+-center" defects that have significant charge in a dark measurement, while changing charge states when illuminated. The contrast between the talks on PECVD highlighted the fact that the optimized PECVD nitride for solar cells, and that for flat-panel displays and integrated circuits, are at very different ends of the spectrum. Cost issues are of particular importance for solar cell applications.

Two innovations that may be useful are a pulsed-mode operation to improve deposition rates with low particle densities, and gas confinement to the plasma regions to improve the gas utilization.

The field of RTP continues to evolve. Talks in this area emphasized the usefulness of this technique for achieving high-quality, Al back-surface fields, selective emitters, and the themal oxidation of silicon. The incorporation of these advances into beltline furnace equipment offers the possibility for a straightforward adoption of this technology in industry. Of key interest was the new understanding of the details of several of the RTP effects. The bulk lifetime is a complex function of the RTA conditions, ambients, and surface condition (phosphorus, Al, bare, or oxidized). It was described how the sheet-rho enhancement of diffusion from spin-on glass dopant sources is an effect on the dopant glass, and NOT an effect on the diffusion kinetics within the silicon. Careful analysis and clever experiments for the case of RTA on an Al-covered wafer indicate that the dominant mechanism determining enhanced P-diffusion in this wafer under RTA conditions is the heat confinement caused by the reduced emissivity of the Al backside. This effect simply results in a higher wafer temperature.

Session 6: Hydrogen Passivation

Open Discussion: Hydrogen in Si: Diffusion and Passivation/Hydrogen Passivation in Multicrystalline Solar Cells

Coordinator: Jack Hanoka

The discussion started with a sort of fact-finding mission in which the session coordinator listed a series of questions and "generally accepted" answers using the following outline.

I. Key defects being passivated: **dislocations**

- Dislocations in Fz passivate ("clean")

- Dislocations in mc-Si are likely decorated ("dirty")
- Not all dislocations in mc-Si passivate—e.g. kinked dislocations, tangles in "bad" regions (Cr. Fe precipitates shown by S. McHugo, bubbles of H shown by B. Sopori)

Question: What passivates at dislocations?

II. Different materials, such as mc-Si, Fz and Cz, exhibit varying passivation behavior, as is demonstrated by the following list of observations (not intended to be comprehensive). How is this to be understood?

- Spiegel *et al.*, Univ. Konstanz, Vienna meeting, July 1998

MIRHP at 350°C

Material	Optimum Process Temperature	Optimum Time
Cast (4 types)	350°–375°C	90–180 min.
EFG (high O)	350°C	30 min.
RGS (high O)	425°C	210 min.

- Effusion studies again show pronounced Si-material dependence

1. Kisielowski-Kemmerich and Beyer, *J. Appl. Phys.* **66**, 552 (1989)
   800°C – H_2 into Fz, effusion bands at 415°, 630° and 900°C
2. Kveder *et al.*, *Phys. Stat. Sol.* (a) **84**, 149 (1984)
   rf plasma @ 350°C – prob. Cz, most effusion at T> 500°C
3. Hanoka *et al.*, *Appl. Phys. Lett.* **42**, 618 (1983)
   Kaufman ion source @ 400°C, EFG ribbon, effusion in range 350°–375°C

III. PECVD SiN Passivation

Plasma - SiH_4 and NH_3 - SiN layer is an alloy with H (≈10% H).

Two-step process for bulk passivation

1. Deposition of SiN at ~400°C
2. Post-deposition anneal at T>>400°C (IMEC, ISFH)

Remote plasma method produces excellent surface passivation (A. Aberle *et al.*, this meeting), but can bulk passivation be improved?

Most people passivate the diffused junction side, but Kyocera passivates both cell sides.

Questions:

- Can bulk SiN with PECVD be further optimized?

- Why is one-side passivation inadequate?

- Diffusion into mc-Si: is it along dislocations, through the lattice, V-H mechanism, trap-limited?

IV. H_2 Passivation

How does the introduction of H work? Sopori *et al.* have suggested that defects at the surface (e.g., damage, dislocations) are required to catalyze $H_2 \rightarrow H$.

- In most mc materials, H_2 passivation is not as effective as PECVD SiN.
- But, A. Rohotgi has shown that a forming gas anneal at 400°C improved the efficiency of EFG solar cells from 10% to 14%.

Question: Why is H_2 passivation less effective?
- Harder to get H in?
- Harder to keep in?

V. Interaction of H with Transition Metals:

Question: Can H passivate them?

An open discussion of hydrogen-passivation issues followed. Several questions were addressed about the forms the hydrogen takes in Si materials, and how it get into samples from a molecular source, and what the mobile species is in the Si lattice.

The session speakers and the coordinator offered the following speculations: Hydrogen probably enters Si as an atomic species. During plasma treatment, atomic H or H^+ ions are readily available. Upon exposure to H_2 gas, presumably the H_2 molecules are dissociated at the Si surface. This dissociation might be facilitated by dislocations, vacancies, the damage associated with surface roughness, metal overlays, and the like. Once inside Si, atomic H is probably the mobile species. Most H probably migrates by trap-limited diffusion with the effective diffusion coefficient determined by the kinetics of hydrogen release from traps. Hydrogen can be bound to a variety of different types of defects or exist in the form of relatively immobile H_2 molecules in the crystal, all of which can potentially act as a reservoir of H.

The following points were also noted in the discussion:

1. The possible similarities of H_2 trapped in platelet defects to H_2 trapped in the voids of

amorphous Si could be of scientific interest.

2. The strong temperature dependence of the hydrogen diffusion coefficient might be important in designing processes in which H was introduced at low temperature and then possibly diffused throughout a solar cell during a later high-temperature step.

Session 7: Thin Silicon Cells

Panel Discussion: *Challenges in Successful Development of Thin Film Si Solar Cell Technology*

Discussion Leader: James Rand

Panel: Harry Atwater, Arun Madan, Juergen Werner, Roland Schindler

Thin-film Si solar cells offer a tremendous promise to lower Si consumption and yield higher efficiencies with moderate material quality for low-cost PV energy production. A great deal of research is devoted to developing mc-Si thin films. Kaneka has already obtained >10% efficiency on 2.5-μm Si films on glass substrates. The major issues in getting higher-efficiency devices are in obtaining larger-grain-size material, compatibility between glass and Si, and very effective light trapping. Some designs indicate a single-junction cell thickness of 10 μm may be necessary to reach 16%–18% efficiency. Much work remains before commercial manufacture of thin-film Si solar cells is feasible. There is, nevertheless, a strong emphasis on reducing the thickness of wafers in the current production lines. Wafer thickness of about 100 μm appears to be reachable in the near future. This raises an argument about whether thin-film cells can actually offer a major advantage over thin-layer cells. A significant part of discussion revolved around this question. This seemed to be important because Astropower is already manufacturing thin-layer (about 50 μm) cells.

Perhaps the importance of thin-film cells will emerge when new approaches based on low-temperature processes such as grain enhancement, high-throughput Si-deposition processes, and detachable films are realized in cell fabrication. Some of these processes can not only lower the PV energy cost, but also decrease energy-payback time.

Wrap Up

Leader: Dick Swanson

The following conclusions and recommendations were voiced during the wrap-up session. As an overall comment, the quality of the poster papers was deemed excellent and these sessions provided much valuable input. The shift in workshop content to include more cell processing was thought to be a positive step. However, it was thought important to maintain the more fundamental scientific, defect-oriented aspect of the workshop, as well. Overall, the workshop was very positively rated, bringing together a wide variety of workers in silicon solar cells. The interchange of information was most useful to all.

A. Feedstock and Wafer Supply Issues

It was concluded that the major issues relating to feedstock are business rather than technical. It is now clear that solar-grade silicon can be manufactured at acceptable costs if the required capital investment in plant and equipment is made. The best path to realization of this investment is an important issue for the industry. However, it was concluded that this is not an appropriate topic for the workshop. Critical technical issues remain over the proper specification of silicon for the PV industry, and this is an important topic that should be further addressed by this workshop. The proper way to specify solar-grade silicon is complicated by the large number of different approaches to cell fabrication being used, each of which has a different response to as-grown impurities and defects, and each of which uses differing amounts of silicon per watt. A comprehensive framework needs to be developed for making progress on this front in order to facilitate the required capital investment.

B. Defects and Impurities

Defect clusters (dead regions) still remain the dominant materials issue in multi-crystalline Silicon. No method has been found as yet to either getter or removes them. Nevertheless, there has been a steady overall improvement in cell performance, which is due to improved starting material and improved gettering procedures. There is hope that RTP will open new avenues to gettering and perhaps allow these improvements to continue for awhile, or perhaps a technique to lessen the impact of the dead regions, without actually removing them, can be found. At this point, the basic physical mechanisms operating during gettering are largely understood and physical models have been developed that describe the many processes operating during gettering. There remains a need to determine the values of many of the parameters in gettering models in order to make them useful in cell design. Recent advancements in the understanding of the diffusion of copper is an example of what can be done with careful physical experimentation. This needs to be done for other common impurities.

It was felt that the workshop should continue to explore the science and technology of those defects in silicon that are relevant to solar cells, along with their control and removal through gettering. There is a crying need to create a clear synthesis of the current understanding of these issues. The large number of complex effects and interactions, involving many different types of impurities and crystalline defects, that occur during solar cell processing will make it difficult to make further progress without first developing a clear, concise picture of the existing state of knowledge.

C. Advanced Diagnostics

The understanding in the use and interpretation of PCD and other lifetime-measuring tools has advanced considerably since the last workshop. It has been demonstrated that SPV, PCD, and LBIC maps are useful and provide complementary information for a variety of materials, such as cast multi-crystalline and ribbon silicon. Progress was made in defining relevant parameters to monitor during processing. Some examples are given the in the following table.

It was felt that the next workshop should begin to facilitate the definition of realistic diagnostic methods and discuss requirements for improved cell-production control. A look at the possibilities for extending existing IC industry tools would be useful, as well as increased understanding of the meaning and interpretation of existing measurements on highly defective materials.

STEP	PROCESS CONTROL PARAMETERS
Wafers	Mechanical, L_{diff}, Resistivity
Texture	Mechanical, Reflectance
Phosphorus Diffusion	Sheet resistivity, J_o, L_{diff}, IQE
Surface Passivation	J_o, L_{diff}, IQE
Al BSF	J_o (front and back), L_{diff}
Metallization	I-V, Sheet resistivity, Shunt resistance, IQE, Adhesion

D. Processing

There has been a big increase in the understanding and use of silicon nitride for surface passivation. This should provide a significant benefit to the industry over the next several years. RTP has continued to improve, pointing to lower-cost processing approaches. Finally, it appears that many effects that were thought to be light-induced are actually just simple thermal effects, based on a new understanding of wafer temperature during RTP. New, cost-effective methods for texturing multi-crystalline silicon are being developed which promise to further narrow the performance gap between single and multi-crystalline cells.

Efficiency records for silicon cells continue to be set. Further improvements in solar cell performance and processing technology are to be expected, and this workshop should remain a forum to present and discuss results. An issue remains in that new, higher-efficiency processes are difficult to introduce into the high-volume, cost-driven solar cell production environment.

E. Hydrogen in Silicon

There has been a huge increase in the understanding of the hydrogen in silicon. The missing hydrogen has been found in the form of molecular hydrogen in the lattice. The diffusion coefficients of different forms of hydrogen are now known with fair certainty. It has been found that metal-hydrogen complexes occur with varying numbers of hydrogen atoms, and that the electrical activity of these complexes depends on the number of hydrogen atoms. This provides important clues to those developing hydrogen-passivation techniques.

It was felt that the time is ripe for an improved synthesis of our understanding of hydrogen-passivation technology. A better understanding of the differing roles of hydrogen at each process step and in different types of material is needed.

F. Thin-Film Si Solar Cell

The progress in thin, deposited silicon cells has been remarkable. It is now known that the theoretical current can be obtained for thin cells with light-trapping. This current is in excess of 30 mA/cm^2. The voltage is still less than desired, but improvements are coming at a fast pace.

Deposited thin silicon solar cells appear to remain an exciting candidate for future, lower-cost cells. It was felt that the small-grained, thin-silicon layers may have similarities with nano-crystalline silicon. The similarities and differences along the continuum between amorphous, nano-crystalline, and small-grained poly-crystalline silicon should be explored in a future workshop.

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13. ABSTRACT *(Maximum 200 words)*

This report is a summary of the panel discussions included with the Eighth Workshop on Crystalline Silicon Solar Cell Materials and Processes. The theme of the workshop was "Supporting the Transition to World Class Manufacturing." This workshop provided a forum for an informal exchange of information between researchers in the photovoltaic and nonphotovoltaic fields on various aspects of impurities and defects in silicon, their dynamics during device processing, and their application in defect engineering. This interaction helped establish a knowledge base that can be used for improving device-fabrication processes to enhance solar-cell performance and reduce cell costs. It also provided an excellent opportunity for researchers from industry and universities to recognize mutual needs for future joint research.

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