SERI/TP-211-2347
UC Category: 63
DE84004591

Research on Crystalline Silicon Solar Cells

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June 1984

Presented at the 17th IEEE
Photovoltaic Specialists Conference
Kissimmee, Florida
1-5 May 1984

Prepared under Task No. 3434.10
FTP No. 462

Solar Energy Research Institute
A Division of Midwest Research Institute

1617 Cole Boulevard
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Prepared for the
U.S. Department of Energy
Contract No. DE-AC02-83CH10093

Printed in the United States of America
Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price:
Microfiche A01
Printed Copy A02

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ABSTRACT

Since the 16th IEEE Photovoltaic Specialists Conference, the focus of the Crystalline Silicon Solar Cell Task at the Solar Energy Research Institute (SERI) has narrowed somewhat. Responsibility for silicon material preparation and ribbon growth were consolidated at the Jet Propulsion Laboratory (JPL) at the end of FY 1983. Five subcontracts were awarded under RFP No. RB-2-02090, "Research on Basic Understanding of High Efficiency in Silicon Solar Cells." JPL and Oak Ridge National Laboratory are also working on high-efficiency solar cell research under SERI subcontract. Reports of past solar cell improvements have prompted appreciable interest in the physical, chemical, and electrical transport properties of grain boundaries and other electrically active defects. Studies to achieve better understanding of the hydrogen passivation process are being conducted at various subcontractors, and our in-house research continues. This paper presents the results of these efforts as well as future directions.

INTRODUCTION

In the previous review of this task, presented at the last IEEE Photovoltaic Specialists Conference (PVSC) (1), we stated, "The Cell R&D area is being transformed into a high efficiency program, with clear objectives and efficiency goals which represent both a risk and an appreciable opportunity. The Basic Mechanisms R&D area is being focused onto the problem of electrically active defects, which represents an opportunity to advance our understanding of some of the fundamental parameters affecting solar cell performance, and their mutual interactions. Novel techniques for passivating at least some of these defects have been found, but remain to be understood. One expects that further advances relating to the science and technology of producing silicon solar cells will be forthcoming, and that in the most favorable circumstance, information obtained from the study of the simplest and best understood semiconductor—silicon—will prove useful as a guide for the study and understanding of the more complicated compound semiconductors."

We will review the results that have been obtained since the time of that writing, which include significant advances in our fundamental understanding of silicon solar cells, demonstrations of how higher conversion efficiencies may be obtained, improvements in our understanding of the phenomenon of passivation of electrically active defects with hydrogen, and an analysis of low-angle silicon sheet (LASS) and edge-supported pulling (ESP) ribbon materials.

PROGRAM ACCOMPLISHMENTS

As a result of RFP No. RB-2-02090, "Research on Basic Understanding of High Efficiency in Silicon Solar Cells," issued in March 1982, subcontracts were awarded to five groups. These include the University of Pennsylvania (Professor M. Wolf, Principal Investigator), the University of Florida (Professor F. A. Lindholm, P.I.), Spire Corporation (Dr. M. B. Spitzer, P.I.), Westinghouse Electric Corporation (Dr. A. Rohatgi, P.I.), and the Joint Center for Graduate Study (JCGS)—University of Washington (Professor L. C. Olsen, P.I.). Oak Ridge National Laboratory (ORNL) (Drs. R. F. Wood and R. T. Young, P.I.) has been studying the properties of silicon solar cells fabricated by glow discharge ion implantation and laser annealing processes for some years under SERI funding. Recently, the Jet Propulsion Laboratory (JPL) (Dr. T. Daud, P.I.) has begun work on a high-efficiency solar cell concept, the Dot Collector cell. Associated with this device will be investigations of voltage enhancement based on reduction of the dark current by reduced p-n junction area and on reduction of surface recombination by the use of limited areas of metal-semiconductor contact. Some of the results obtained in these programs are presented in chronological order below.

In January 1983, SERI measured cells fabricated by the ORNL group at 16.5% conversion efficiency (2). At that time, these were the most efficient silicon cells ever measured at SERI. While others had claimed higher cell efficiencies before, which we take no issue with, we were not given the opportunity to measure them.

In May 1983, K. S. Ling of Applied Solar Energy Corporation (ASEC) provided us with six silicon cells, each approximately 4 cm^2, to be tested at SERI. The results we obtained are given in Table 1 (3). This was the first response to SERI's standing offer to test highly efficient silicon cells, whether or not SERI supported the fabrication of the devices. In this instance, our results disagreed with the measurements made on these devices by ASEC (4) in two respects. First, ASEC defined the area of these cells as 4.00 cm^2, based on the area scribed by a laser, while our area measurements on the cells consisted of measuring the actual chip length and width with a vernier caliper and multiplying. Second, different standard cells were used in measuring these devices in each location.

Table 1. Results of Measurements on ASEC Cells (May 1983)

Sample No.	Area (cm^2)	J_{sc} (mA/cm^2)	V_{oc} (mV)	FF (%)	Efficiency (%)
1	4.070	34.75	620.7	78.05	16.84
2	4.062	34.58	618.6	79.88	17.09
3	4.068	34.72	619.6	79.24	17.05
4	4.062	34.02	621.8	79.92	16.90
5	4.070	33.86	622.8	79.11	16.68
6	4.056	34.75	620.2	79.33	17.10

Our measurements differed by 4% (relative), which might be explained by the 2% relative difference in areas assumed, and the possible differences in measurement apparatus.

In August 1983, six cells (approximately 1 cm^2) fabricated at Westinghouse (SERI Subcontract XB-3-02090-4) on 4 ohm-cm, boron-doped, (111) 10-mil-thick, float-zone silicon were measured at SERI. Five of these cells demonstrated efficiencies of 17% or above (5). The results obtained at SERI are presented in Table 2. In the Westinghouse program, more recent achievements include calculation of the reflectance that might be attained using a double-layer antireflection coating, the fabrication of such coatings, and the measurement of the reflectance, which agreed very well with predicted values.

In September 1983, four 4-cm^2 solar cells fabricated at Spire Corporation (SERI Subcontract ZB-3-02090-3) were measured at SERI on 0.2 ohm-cm, boron-doped, (100) 15.2-mil-thick, float-zone silicon. Using ion implantation, thermal anneals, surface passivation, and surface texture, one cell from this group exhibited 18% conversion efficiency (6,7). The cells were all remeasured at JPL on three additional simulators (with the kind cooperation of Bob Weiss, Bob Meuller, and Gerry Crotty), using the same standard cell that had been used at SERI. While the 18% cell was found to have suffered a fill factor degradation (subsequently confirmed by remeasurement at SERI), the other three cells responded as expected. In November 1983, two additional cells from the same group were delivered to SERI that exhibited 17.9% and 18.0% efficiency. The results of these measurements are presented in detail in Table 3 (8).

In late 1983, seven MINP silicon solar cells fabricated (without SERI funding) by M. Green and coworkers (9) on 0.1 and 0.2 ohm-cm, boron-doped, float-zone silicon

Table 2. Results of Measurements on Westinghouse Cells (August 1983)

Sample No.	Area (cm^2)	J_{sc} (mA/cm^2)	V_{oc} (mV)	FF (%)	Efficiency (%)
HIEFY-4-4	1.01	35.5	604	79.6	17.1
-5	1.01	35.6	604	79.5	17.1
-6	1.01	35.9	605	78.6	17.1
-7	1.01	35.4	604	79.7	17.0
-8	1.01	35.3	603	79.8	17.0
-11	1.01	35.5	604	76.1	16.3

Table 3. Results of Measurements on Spire Cells (September 1983)

Sample No.	Area (cm^2)	J_{sc} (mA/cm^2)	V_{oc} (mV)	FF (%)	Efficiency (%)
SD2219	4.01	35.7	618	80.0	17.6
SD2220	4.00	36.1	622	80.1	18.0
SD2221	4.01	36.3	616	78.0	17.5
SD2222	4.01	36.0	619	79.1	17.6

(November 1983)

Sample No.	Area (cm^2)	J_{sc} (mA/cm^2)	V_{oc} (mV)	FF (%)	Efficiency (%)
SD2220	4.00	36.0	620	78.0	17.4
SD2252	4.00	36.0	621	80.1	17.9
SD2253	4.00	36.2	622	80.1	18.0

at the Solar Photovoltaic Laboratory, University of New South Wales, Kensington, Australia, were measured at SERI. These cells ranged in efficiency from 18.1% to 19.1% (see Table 4). We believe that this is the highest efficiency measured for a silicon device operating under one-sun conditions. These results have been corroborated in part by further tests at Sandia National Laboratory. This work at UNSW has been supported by NASA-Lewis Research Center as well as by the Australian Government.

On March 6, 1984, we measured a 4-cm^2 MINP device fabricated by JCGS (SERI Subcontract XB-2-02090-5) on 0.2 ohm-cm, boron-doped, (100) float-zone silicon that exhibited 15.6% efficiency, and on March 13, we measured another 4-cm^2 cell that demonstrated 16.8% efficiency (10). The major difference between these cells is that the former was not textured and the latter had a surface texture. While these results, shown in Table 5, are not as remarkable as those of Green, it should be noted that JCGS had achieved only an 11.7% efficiency at the time of the last PVSC.

While the groups at the University of Pennsylvania and the University of Florida have both performed useful theoretical and experimental research in the area of device analysis (11,12), their efforts at producing high-efficiency cells have been hindered by a lack of in-house fabrication capabilities. Both groups have depended on others for cell fabrication, which has caused considerable delays.

Investigations of electrically active defects in polycrystalline and single-crystal materials, have advanced appreciably since the last PVSC. At that meeting, results on the hydrogen passivation of EFG ribbon (13) and Wacker Silso (14) were reported. Passivation results using hydrogen ion bombardment have been obtained on dendritic web (15-17) and on ESP (16) ribbon in the meantime, and they are presented in other papers at this meeting. A kinetic theory of the hydrogen passivation process for polycrystalline silicon devices has been developed by Ginley and coworkers at Sandia (18) which will also be presented at this meeting. On the whole, we can safely draw a few general conclusions based on results to date. First, the conditions required to optimally treat silicon solar cells fabricated on different materials are different and are quite dependent on the material being treated. Second, absolute efficiency improvements of approximately 1.5% (and relative improvements of from 10% to 30%) have been obtained by various groups treating a variety of materials.

Subcontracts were awarded to the University of Florida (Professor P. Holloway, P.I.) and Cornell University (Professor D. G. Ast, P.I.) as a result of RFP No. RB-2-02129, "Investigation of Selected Electrically Active Defects in Polycrystalline Silicon Solar Cell Materials." These groups will investigate the structure, chemistry, and electrical transport properties of selected defects such as grain boundaries, using techniques that will include transmission electron microscopy, EBIC, and chemical analysis. A subcontract was also awarded to JPL (Dr. L. J. Cheng, P.I.) to study the properties of tilt boundaries in bicrystals deliberately grown with selected tilt angles. This study will include EBIC analysis as well as DLTS measurements. Some work in this area has also been underway in-house at SERI and interesting results have been obtained on the structure of ESP and LASS silicon ribbons (19), the effects of electron beams on hydrogen in silicon samples (20), and the crystal growth mode that appears to have to exist when LASS twin-stabilized (essentially single-crystal) ribbon grows (21).

Future plans in the Crystalline Silicon Solar Cell Task include initiating a multiwafer sequential processing investigation that will be carried out on high-quality, float-zone silicon by the high-efficiency cell processing groups. A variety of processes are being investigated, such as ion implantation/laser anneal (ORNL), ion implantation/thermal anneal (Spire), diffusion (Westinghouse), and MINP (JCGS). This investigation will shed some light on the defects induced in float-zone silicon or modified by various fabrication techniques. We expect that efficiencies above 20% will be demonstrated in the near future (probably before the next PVSC); in fact, recent analyses by a number of groups (22,23) indicate

Table 4. Results of Measurements on UNSW Cells (December 1983)

Device No.	Area (cm^2)	J_{sc} (mA/cm^2)	V_{oc} (mV)	FF (%)	Efficiency (%)
129	4.09	660	34.5	79.8	18.1
120	4.07	640	36.1	81.0	18.7
78	4.01	643	36.0	80.8	18.7
13AA	4.08	650	36.2	80.0	18.8
13BB	4.08	652	36.3	80.2	19.0
177	4.08	653	36.0	80.8	19.0
176	4.07	653	36.0	81.1	19.1

Table 5. Results of Measurements on JCGS Cells

Sample No.	Date	Area (cm^2)	V_{oc} (mV)	J_{sc} (mA/cm^2)	FF (%)	Efficiency (%)
83SiNP20	9/12/83	3.95	634	30.7	77.5	15.1
84SiNP4	3/6/84	3.97	636	31.1	78.7	15.6
84SiNP6	3/13/84	3.94	617	35.5	76.8	16.8

that efficiencies approaching 25% may be realistic. Further work needs to be done, both experimentally and theoretically, on understanding the mechanism of hydrogen passivation: how the hydrogen acts on defects, where it is located, and why very different energies are needed to incorporate hydrogen into different types of silicon samples. More pragmatically, determining the optimal conditions for passivation of real devices will also be an important issue. The efficacy of hydrogen passivation on very efficient (for example, greater than 16%) cells will also be investigated. We will pursue the study of structural, chemical, and electronic transport properties of electrically active defects, including studies of the effects of thermal processing, in support of the high-efficiency component of the task.

CONCLUSIONS

Significant progress in understanding and demonstrating high efficiency in silicon solar cells has been achieved, and further improvements are expected. Excellent results are being attained by a number of groups, not all of whom are being supported by SERI. The High Efficiency RFP was motivated by the conceptions that (1) an "existence proof" (i.e., a demonstrable cell exhibiting above 17% efficiency by the largest amount practical) would prompt non-SERI-supported groups to perform research which would lead to improved products, based on the knowledge that improvements in efficiencies are attainable; and that (2) analysis and understanding, rather than empiricism, are needed to reach the limits of efficiency that we suspect are attainable. We hope that the results reported at this meeting will convince others of the utility of such research.

Our understanding of the hydrogen passivation process in crystalline silicon is also increasing at a rapid pace, although much more remains to be learned. We are only at the very earliest stages of unraveling the intricacies of the roles of structure, chemistry, and physics of electrically active defects. If we can learn to control such defects, this discovery may prove exceedingly valuable, both in allowing us to prepare cells of the highest quality and in providing a model that may be useful in the study and application of more complex materials.

ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy under Prime Contract No. DE-AC02-83CH10093.

REFERENCES

1. J. B. Milstein, R. W. Hardy, and Y. S. Tsuo. Proc. 16th IEEE PV Spec. Conf. (IEEE, New York, 1982) p. 119.
2. R. T. Young et al., Appl. Phys. Lett. 43, 666 (1983).
3. J. B. Milstein, paper presented at the Photovoltaics Advanced Research and Development 5th Annual Meeting, Denver, Colo., May 19-21, 1983.
4. F. Ho and P. Iles, "High Efficiency Silicon Solar Cells" (these proceedings).
5. A. Rohatgi, P. Rai-Choudhury, D. L. Meier, and J. B. Milstein, "Surface-Passivated High-Efficiency Silicon Solar Cells" (these proceedings).
6. M. B. Spitzer, Proceedings of the 22nd Project Integration Meeting (JPL, Pasadena, Calif., 1984) p. 473.
7. J. B. Milstein, in Ref. 6, p. 511.
8. M. B. Spitzer, C. J. Keavney, S. P. Tobin, and J. B. Milstein, "Ion Implanted Silicon Solar Cells with 18% Conversion Efficiency" (these proceedings).
9. M. A. Green, A. W. Blakers, S. Jiqun, E. M. Keller, S. R. Wenham, R. B. Godfrey, T. Szpitalak, and M. R. Willison, "Towards a 20% Efficient Silicon Solar Cell" (these proceedings).
10. L. C. Olsen, F. W. Addis, W. A. Miller, and G. Dunham, "High-Efficiency Silicon MINP Solar Cells" (these proceedings).
11. M. Wolf, M. Newhouse, and R. J. Stirn, "Si CVD-Epitaxial Layers for High-Efficiency Solar Cells" (these proceedings).
12. F. A. Lindholm and C. T. Sah, "Theoretical Performance Limits and Measured Performance of Thin Extended BSF p/n Junction Silicon Solar Cells" (these proceedings).
13. J. I. Hanoka, C. H. Seager, D. J. Sharp, and J. K. G. Panitz, Appl. Phys. Lett. 42, 618 (1983).
14. W. Schmidt, K. D. Rasch, and K. Roy, Proc. 16th IEEE PV Spec. Conf. (IEEE, New York, 1982) p. 537.
15. R. Singh, S. J. Fonash, A. Rohatgi, and P. Rai-Choudhury, Proc. 5th European Communities Photovoltaic Solar Energy Conference (D. Reidel Publishing Company, Dordrecht, 1984), p. 1064.
16. J. B. Milstein, Y. S. Tsuo, C. R. Osterwald and C. W. White, "Hydrogen Passivation of Electrically Active Defects in Crystalline Silicon Solar Cells" (these proceedings).
17. D. L. Meier, R. B. Campbell, A. Rohatgi, P. Alexander, S. J. Fonash, and R. Singh, "Emitter Formation in Dendritic Web Silicon Solar Cells" (these proceedings).
18. D. S. Ginley, D. M. Haaland, and R. P. Hellmer, "Kinetic Modeling for Grain Boundary Passivation of Polycrystalline Silicon" (these proceedings).
19. Y. S. Tsuo and R. J. Matson, "Electron Channeling and EBIC Studies of Polycrystalline Silicon Sheets" (these proceedings).
20. B. G. Yacobi, R. J. Matson, C. R. Herrington, and Y. S. Tsuo, "Limitations to the Application of the Electron-Beam-Induced Current in Hydrogen-Passivated Silicon Grain Boundaries," submitted to J. Appl. Phys. Communications.
21. Y. S. Tsuo, J. B. Milstein. R. J. Matson, and T. Schuyler, "Investigation of Structural and Electrical Properties of Low-Angle Silicon Sheets," to be presented at the Sixth American Crystal Growth Conference, Atlantic City, New Jersey, July 15-20, 1984.
22. T. Tiedje, E. Yablonovitch, G. D. Cody, and B. G. Brooks, "Limiting Efficiency of Silicon Solar Cells," IEEE Trans. on Electron Devices (in press).
23. V. G. Weizer, C. K. Swartz, R. E. Hart, and M. P. Godlewski, "Voltage-Controlling Mechanisms in Low Resistivity Silicon Solar Cells—A Unified Appoach," IEEE Trans. on Electron Devices (in press).