Energy

S
O
L
A
R

525
12/11/84

mjr

(3) DR-0670-X

DOE/JPL/956786-84/1
(DE85001383)

DEVELOPMENT OF HIGH-EFFICIENCY SOLAR CELLS
ON SILICON WEB

First Quarterly Progress Report for the Period April 20—July 15, 1984

By
A. Rohatgi
D. L. Meier
R. B. Campbell
P. Rai-Choudhury

August 9, 1984

Work Performed Under Contract No. NAS-7-100-956786

Westinghouse R&D Center
Pittsburgh, Pennsylvania

Technical Information Center
Office of Scientific and Technical Information
United States Department of Energy

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

This report has been reproduced directly from the best available copy.

Available from the National Technical Information Service, U. S. Department of Commerce, Springfield, Virginia 22161.

Price: Printed Copy A02

Microfiche A01

Codes are used for pricing all publications. The code is determined by the number of pages in the publication. Information pertaining to the pricing codes can be found in the current issues of the following publications, which are generally available in most libraries: *Energy Research Abstracts (ERA)*; *Government Reports Announcements and Index (GRA and I)*; *Scientific and Technical Abstract Reports (STAR)*; and publication NTIS-PR-360 available from NTIS at the above address.

DEVELOPMENT OF HIGH-EFFICIENCY
SOLAR CELLS ON SILICON WEB

A. Rohatgi, D. L. Meier, R. B. Campbell,
and P. Rai-Choudhury

First Quarterly Progress Report
April 20 to July 15, 1984

This work was performed for the
Jet Propulsion Laboratory

August 9, 1984

Westinghouse R&D Center
1310 Beulah Road
Pittsburgh, Pennsylvania 15235

MASTER

CONTENTS

	Page
LIST OF FIGURES.....	ii
1. SUMMARY.....	1
2. INTRODUCTION.....	3
3. TECHNICAL PROGRESS.....	5
3.1 Model Calculations for Understanding the Effect of Electrical Activity of the Twin Plane on V_{oc}	5
3.2 LBIC Measurements on Beveled Web Surfaces.....	8
3.3 Effect of Heat Treatment on the Minority Carrier Diffusion Length in Web.....	12
3.4 Effect of Solar Cell Processing on Minority Carrier Diffusion Length in Web.....	15
4. PROGRAM STATUS.....	18
4.1 Present Status.....	18
4.2 Future Activity.....	18
5. REFERENCES.....	20
6. ACKNOWLEDGEMENTS.....	21

LIST OF FIGURES

	Page
Figure 1. Model calculations for the effect of electrical activity of the twin plane on V_{oc} in 4 ohm-cm web cells.	6
Figure 2. Model calculations for the effect of electrical activity of the twin plane on V_{oc} in 0.2 ohm-cm web cells.	7
Figure 3. Sensing the electrical activity of the twin plane with light-beam-induced current (LBIC).	10
Figure 4. Photograph (50X) of beveled surface partially etched to reveal location of twin planes.	11
Figure 5. Schottky diode characteristics on web samples illustrating that beveled surface need not introduce excessive leakage current.	13
Figure 6. LBIC scan of beveled surface indicating that the photoresponse of one side of the twin plane is stronger than the photoresponse on the other side.	14

1. SUMMARY

The major objective of this contract is to improve web base material with a goal toward obtaining solar cell efficiencies in excess of 18% (AM1). The program consists of the investigation of carrier loss mechanisms in web silicon, development of techniques to reduce carrier recombination in web, and web cell fabrication using effective surface passivation.

In the first quarter of this program we have learned how to bevel web surfaces with the intention of measuring the electrical activity of the twin plane. Helium-neon laser-beam-induced current (LBIC) measurements have been performed on beveled web surfaces. Our first measurement showed that the two sides of the twin plane have different photoresponse, although there was no evidence of poor photoresponse right at the twin plane in this sample. More experiments are being conducted to verify this observation and to check if beveling-induced damage is responsible for such photoresponse. We have also grown web crystals intentionally contaminated with vanadium and titanium impurities to examine the twin-plane-assisted internal gettering by DLTS measurements. These web crystals have been beveled and Schottky barrier diodes are being fabricated on the beveled surfaces. DLTS measurements on these Schottky diodes will tell us if the twin plane getters contaminants and acts as a loss mechanism in web solar cells.

We have done model calculations to see the effect of twin-plane activity on V_{oc} as a function of resistivity of the web material. The calculations indicate that an active twin plane can lower V_{oc} . The impact of an active twin plane on 4 ohm-cm web cell efficiency is much more than on 0.2 ohm-cm web cells because the V_{oc} of a 4 ohm-cm cell is

base limited, while in 0.2 ohm-cm cells the emitter usually limits the V_{oc} .

Experiments to study the effect of that treatment and gettering on the minority carrier diffusion length in web have been initiated. The first experiment showed that the diffusion length improves after 800-900°C heat treatments, but it drops sharply after a 1100-1200°C heat treatment in oxygen. Some other web crystals, however, showed that a 1100-1200°C heat treatment also improves the diffusion length. More experiments are in progress to resolve this controversy.

We have initiated a run to fabricate high-efficiency web cells using several web crystals. These cells will include surface passivation and double-layer antireflection coating. In order to understand the recombination and loss mechanisms in web, we are measuring the diffusion length after each high-temperature process step. The diffusion length in some cases decreases but in others it improves. This area needs further investigation to understand the process-induced effect on web quality.

The first web solar cell run should be completed within the next two weeks, and we should be able to correlate cell performance with the diffusion length before, during, and after cell processing. This correlation should give us much better insight into the web material and its response to various processing steps.

Thus, an improved understanding of the twin-plane activity, twin-plane-assisted internal gettering, starting web quality, and the effect of heat treatment on minority carrier lifetime in the web silicon will provide us with the guidelines to achieve the goal of 18% efficient web cells.

2. INTRODUCTION

The idealized efficiency⁽¹⁾ of a silicon solar cell is about 25%, assuming the best material and surface parameters achievable to date, although present day cells fall considerably short of this limiting value. This is largely a consequence of heavy doping effects, bandgap narrowing, and high recombination at and near the cell surfaces. The major problems of efficiency improvement fall in the above categories; however, there are additional design requirements for efficient contacts and antireflective coating. Although these areas are well understood, they are not trivial and must be optimized consistent with the device structure.

Starting material is equally important for high-efficiency cells because device fabrication and design are academic if the starting material quality is poor or it degrades rapidly with processing. The objective of this program is to understand and improve web silicon so that high-efficiency web cells can be fabricated using advanced cell design and processing.

It is clear that high efficiency is a major attribute that will enhance the large-scale applicability of photovoltaic systems. Systems calculations indicate that for very large-scale terrestrial applications, >15% efficient photovoltaic modules will be required at a cost of ~50¢/watt. This implies that ~18% efficient cells will be needed at low cost. Dendritic web silicon is a single-crystal silicon ribbon that has great potential for low-cost and high-efficiency solar cells. In this program we are trying to understand the loss mechanisms in dendritic web silicon by investigating the electrical activity of twin planes, the role of impurities and defects in web, impurity interaction with twin planes, starting web material quality, and the

effect of heat treatment and gettering on web quality. An improved understanding of the above effects should enable us to fabricate ~18% efficient web cells with good uniformity. In this report we describe our progress toward the development of high-efficiency solar cells on web silicon.

3. TECHNICAL PROGRESS

3.1 Model Calculations for Understanding the Effect of Electrical Activity of the Twin Plane on V_{oc}

We have used our simple analytical model⁽¹⁾ to examine the effect of electrical activity of twin plane on V_{oc} . From the model calculations we plot the recombination velocity as a function of distance into the cell. In Figure 1, a plot of S is shown on the 4 ohm-cm, 150 μ m thick base of the web with a diffusion length of 104 μ m and a back-surface (p-p⁺) recombination velocity of 1000 cm/sec. Assuming that V_{oc} is base limited, we have calculated

$$V_{oc} = \frac{q n_i^2}{N_A} S_{ej}$$

where S_{ej} is the recombination velocity on the base side of the junction edge.

In order to model the effect of the twin plane, we have assumed different recombination velocities ranging from 10 to 10^6 cm/sec at the twin plane. It is clear from Figure 1 that for $S > 5 \times 10^3$ cm/sec the twin plane lowers V_{oc} , and for $S < 5 \times 10^3$ cm/sec the twin plane can increase V_{oc} , although the latter is not possible unless the twin plane is passivated by some special technique. For example: (a) without any twin plane activity, V_{oc} is 0.551 volts; (b) with $S = 10^6$ cm/sec, V_{oc} is reduced to 0.537 volts; and (c) with $S = 10$ cm/sec, V_{oc} increases to 0.562 volts.

Figure 2 shows similar calculations for a low-resistivity (0.2 ohm-cm) web cell with a diffusion length of 104 μ m and a cell thickness of 150 μ m. The calculated values of V_{oc} in Figure 2 assume that the V_{oc} is base limited ($J_{ob} \gg J_{oe}$), which is only true for a cell

Figure 1. Model calculations for the effect of electrical activity of the twin plane on V_{OC} in 4 ohm-cm web cells.

Figure 2. Model calculations for the effect of electrical activity of the twin plane on V_{oc} in 0.2 ohm-cm web cells.

with a very good emitter, where the emitter surface is properly passivated and the heavy doping effects are reduced. Without these features V_{oc} is usually emitter limited ($J_o \sim J_{oe}$) for such low-resistivity cells.^(3,4) If the V_{oc} is emitter limited then the twin plane will not have much affect on V_{oc} because $J_{oe} \gg J_{ob}$ and the twin plane can only influence J_{ob} .

Figure 2 indicates that in the case of a base-limited V_{oc} , even with a highly active twin plane ($S = 10^6$ cm/sec), V_{oc} on the order of 638 mV can be realized in the low-resistivity cells. A highly active twin plane in the 4 ohm-cm cell resulted in a V_{oc} of only 537 mV. Since in these calculations the diffusion length is assumed to be the same in 4 ohm-cm as well as 0.2 ohm-cm cells, J_{sc} will essentially be the same for both cases, although the 0.2 ohm-cm cell may show slightly low J_{sc} due to smaller diffusivity (D).

Therefore, the above model calculations suggest that if the same diffusion length can be obtained in 4 ohm-cm and 0.2 ohm-cm web cells (which is possible if an external source, like an impurity or defect, limits the value of L rather than the dopant concentration), then low-resistivity material will not only give much higher efficiency cells, but any adverse affect of twin-plane activity on V_{oc} will also be mitigated or eliminated.

3.2 LBIC Measurements on Beveled Web Surfaces

Light-beam-induced current on beveled surfaces is being conducted to see if the twin plane is electrically active and if the variation in twin plane activity can account for the spread in web cell efficiency. In order to conduct these measurements, samples of dendritic web silicon were cut to a 2 x 5 mm size and the samples were beveled at an angle of $20^\circ 52'$. The beveling was done with the sample mounted on a spreading resistance beveling block using 0.25 μ m diameter diamond paste followed by a syton polishing to remove mechanical damage to the beveled surface. The back was lapped with 1 μ m diameter alumina

powder for ohmic contact. The location at which the twin planes emerge from the beveled surface was revealed by a Sirtl etch for four minutes. During the Sirtl etch, most of the beveled surface was protected by black wax. This technique is effective in locating the twin planes while leaving the polished beveled surface unharmed and ready for deposition of aluminum for a Schottky diode.⁽²⁾

A Schottky diode is formed on the beveled surface as well as on the as-grown surface on the top by evaporation of a 100 Å thick aluminum layer (Figure 3). This aluminum layer is thin enough to transmit an appreciable fraction of the light from a helium-neon laser source. The electrons and holes created by the absorbed light are separated by the depletion field of the Schottky diode. At a wavelength of 633 nm, the absorption depth of the He-Ne light is $\sim 3 \mu\text{m}$, so only the quality of the web material near the surface is sampled.

The back surface is lapped to allow the formation of an ohmic contact when a $1 \mu\text{m}$ thick layer of aluminum is deposited. The end result is the formation of a large-area Schottky diode, as shown in Figure 1. A laser spot is raster scanned along the beveled surface and the photoresponse signal is recorded on a photograph. If the twin plane is acting as a plane of high recombination, then the photocurrent is expected to decrease as the beam passes over the twin plane, as shown in Figure 3. An attractive feature of this approach is that the twin plane is exposed at the beveled surface, so that its effect can be sensed in a direct way.

A photograph of a typical beveled sample is shown in Figure 4 with the twin planes as indicated. The irregular line in Figure 4 separates the part of the sample that was etched (left) from that which was protected from the etch (right). Note that the etched region is reasonably smooth, suggesting that surface damage created by the beveling process is not excessive.

A 100 Å layer of aluminum was evaporated over the unetched portion of the surface shown in Figure 4 to create a Schottky diode with a semitransparent contact metal. The I-V characteristics of such a

Dwg. 9357A98

Figure 3. Sensing the electrical activity of the twin plane with light-beam-induced current (LBIC).

Figure 4. Photograph (50X) of beveled surface partially etched to reveal location of twin planes.

Schottky diode are shown in Figure 5, along with an I-V curve for a Schottky diode formed on the as-grown web surface, without a bevel. The fact that the leakage currents are low and comparable for both Schottky diodes is further indication that the beveling does not introduce excessive surface damage.

Thus far only a few beveled web samples have been examined by the scanned laser-beam-induced current (LBIC) technique. A He-Ne laser is used. With a wavelength of 6328 Å and an absorption depth in silicon of 3 µm, only the near-surface region is sensed. The most interesting result to date is shown in Figure 6, where it is seen that the twin plane forms a boundary between two regions having different photoresponse. This suggests that the quality of the silicon, in some web material, may differ from one side of the twin plane to the other. This may be because the twin plane blocks the movement of dislocations. Thus, if more dislocations are introduced into material on one side of the twin plane than on the other side, perhaps during web growth, then this asymmetry is preserved by the blocking action of the twin planes. If the dislocations become electrically active, possibly by being decorated by impurities, then the observed LBIC photoresponse is what one would expect to see. Further LBIC measurements are in progress.

3.3 Effect of Heat Treatment on the Minority Carrier Diffusion Length in Web

The starting quality of silicon for fabricating solar cells is important, but even more important is what happens to that material as a result of cell processing. If the minority carrier diffusion length degrades sharply as a result of high-temperature cell processing, then the starting material quality becomes academic. On the other hand, some material may show improvement as a result of heat treatment or gettering (POCl₃ diffusion) because such treatments may release stress, allowing quenched-in mobile impurities or defects to migrate away from the bulk to the surfaces where they can be gettered.

a) Aluminum on beveled surface

b) Aluminum on as-grown surface

Figure 5. Schottky diode characteristics on web samples illustrating that beveled surface need not introduce excessive leakage current.

Figure 6. LBIC scan of beveled surface indicating that the photo response of one side of the twin plane is stronger than the photoresponse on the other side.

In order to investigate the effects of heat treatment on web silicon, we divided a web crystal into several small pieces and subjected them to dry oxidation in the temperature range of 800°C-1200°C. Each sample was subjected to only one oxidation, after which the samples were slow cooled in N₂ at 1°C/min to 600°C. The minority carrier diffusion length before and after heat treatment was measured by the surface photovoltage technique.

Results of the first heat treatment experiment on web crystal number 1.288-7.3 are shown in Table 1. Prior to any heat treatment (Sample #6), this crystal had a diffusion length of only 25 μm. After an 800 or 900°C heat treatment (which is close to our cell-processing temperature), the diffusion length went up to 73 μm. After a 1000°C/1 hour heat treatment, the diffusion length went up from 25 μm to 61 μm. However, after a 1100°C or 1200°C heat treatment, the diffusion length dropped below 10 μm. At 1200°C, even 5% HCl gettering (Sample #7) could not bring the diffusion length above 25 μm. This is an interesting result, illustrating that at various cell-processing temperatures the diffusion length improves in web silicon. We do not fully understand the mechanism behind this thermal response, and more experiments are being conducted to check the reproducibility of such data on different web crystals. Stress release or migration of quenched-in impurities to the surfaces can be responsible for the observed lifetime enhancement after an 800 to 1000°C oxidation. On the other hand, oxidation-induced stacking faults at higher temperatures may be responsible for the reduced lifetime after an 1100-1200°C heat treatment.

3.4 Effect of Solar Cell Processing on Minority Carrier Diffusion Length in Web

We have initiated a couple of solar cell runs to fabricate high-efficiency web cells. These cells will have surface passivation and double-layer antireflection coating. We are tracking the minority carrier diffusion length by surface photovoltage measurement after each

process step to understand the process-induced effect on web quality and to develop processes that will enable us to fabricate high-efficiency web cells.

The first web cell run has gone through various diffusions and oxide passivation and is being AR coated and metallized. This run consists of several different web crystals. Table 2 shows how the diffusion length changed in each crystal after the diffusions and oxidation. In this table we do not have the data after boron BSF diffusion, which is the first high-temperature (960°C) step prior to POCl_3 diffusion.

Table 1
EFFECT OF SOLAR CELL PROCESSING ON MINORITY
CARRIER DIFFUSION LENGTH IN WEB SILICON
(HIEFY-16 Web)

Sample ID	Crystal ID	As-Grown L(μm)	After POCl_3 L(μm)	After Passivation L(μm)
38	0006-5.10	82	60	38
44	6240-6.4	15	17	7
46	3128-12.8	173	96	52
48	3128-13.4	67	79	70
93	6241-4.3	21	21	6.6
96	0006-10.6	88	41	60

Table 2
EFFECT OF HEAT TREATMENT ON MINORITY CARRIER
DIFFUSION LENGTH IN WEB SILICON
(Crystal ID - 89,1.288-7.3)

All samples were heat treated in O_2 and slow cooled at 1°C/min to 600°C in N_2

Sample ID	Oxidation Temperature	SPL-Diffusion Length
1	800°C/1 hour	73 μm
2	900°C/1 hour	70 μm
3	1000°C/1 hour	61 μm
4	1100°C/1 hour	9 μm
5	1200°C/1 hour	0.5 μm
6	No heat treatment	25 μm
7	1200°C/1 hour/5% HCl	18 μm

The data in Table 2 indicate that some of these crystals had good diffusion lengths to begin with (Sample numbers 38, 46, and 96), but they went down at the end of POCl_3 treatment. Sample number 48 with a starting diffusion length of 67 μm showed a slight improvement, and sample numbers 44 and 93, which had low starting diffusion lengths, did not show any appreciable change after POCl_3 treatment. This observation is somewhat different than what we saw in Table 1, where the lifetime increased after the 800-1000°C heat treatment. More experiments and statistics are needed to understand these differences. Table 2 also shows that after oxide passivation, the diffusion length decreases further in most samples used in this run. These cells should be completed in a couple of weeks, and then we will correlate the web cell performance with the diffusion length map for each crystal.

We also followed the diffusion length of a good-quality, 0.25 ohm-cm, 375 μm thick, (100) float-zone wafer as a function of the cell-processing steps. Table 2 shows (sample number FZ) that there is no change in the diffusion length of this float-zone silicon as a result of cell processing. This is an important fact because it shows that our cell processing is excellent and does not introduce any lifetime-killing centers. It also suggests that dendritic web silicon crystals show changes in lifetime due to cell processing probably because of additional features such as twin planes, dislocations, stress, high oxygen content, residual impurities, or native or process-induced defects. The most confusing issue at the moment is that some of the web crystals show an increase while others show a decrease after the same heat treatment. More experiments are in progress to resolve these issues and provide guidelines for making high-efficiency cells.

4. PROGRAM STATUS

4.1 Present Status

The current milestone chart for this program is shown in Table 3.

During this period we have:

- Modeled the effect of the twin plane on V_{oc} .
- Performed a few He-Ne laser-beam-induced current (LBIC) measurements on beveled web surfaces to detect electrical activity of the twin plane.
- Initiated a web solar cell run.
- Conducted experiments to investigate the effect of heat treatment, gettering, and cell processing on web silicon.

4.2 Future Activity

We plan to conduct more LBIC measurements to examine the electrical activity of the twin plane. We will complete web cell fabrication runs and start examining the impurity/twin-plane interaction by DLTS. We plan to continue the investigation of heat-treatment effects on web silicon.

Table 3
MILESTONE CHART

5. REFERENCES

1. A. Rohatgi and P. Rai-Choudhury, IEEE Transactions on Electron Devices, ED-31, No. 5, p. 569 (1980).
2. A. Rohatgi, D. L. Meier, R. B. Campbell, and P. Rai-Choudhury, Second Monthly Report on "Development of High-Efficiency Solar Cells on Silicon Web," JPL Contract No. 956786.
3. A. Rohatgi, D. L. Meier, and P. Rai-Choudhury, "Surface-Passivated High-Efficiency Solar Cells," Proc. 17th IEEE Photovoltaic Specialists Conf., Orlando, FL, May 1984.
4. J. G. Fossum, F. A. Lindholm, and M. S. Shibib, IEEE Trans. on Electron Devices, Vol. ED-26, p. 1294 (1979).

6. ACKNOWLEDGEMENTS

The authors would like to thank J. B. McNally, F. S. Youngk, and G. J. Machiko for cell fabrication; D. N. Schmidt and W. Cifone for the preparation of beveled web pieces of LBIC measurements; T. W. O'Keefe for assistance with the LBIC measurements; S. Karako for surface photovoltage measurements and assisting with the model calculations; and G. S. Law for reading and preparing the manuscript.