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LARGE-AREA SHEET TASK ADVANCED DENDRITIC
WEB GROWTH DEVELOPMENT

Quarterly Report for the Period October 23—December 31, 1983

By
C. S. Duncan
R. G. Seidensticker
J. P. McHugh

March 6, 1984

Work Performed Under Contract No. NAS-7-100-955843

Westinghouse R&D Center
Pittsburgh, Pennsylvania

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Contract No. 955843

The JPL Flat Plate Solar Array Project is sponsored by the U. S. Dept. of Energy and forms part of the Solar Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays. This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, by agreement between NASA and DOE.

March 6, 1984

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

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1. SUMMARY

Two types of design concepts were evaluated with the thermal models: (1) a vertical thermal element which modifies both the temperature profile in the web as well as the convective gas flow near the web and (2) a thinner lid configuration in which the second lid is replaced by a hot cavity. Each involves trade-offs which need experimental evaluation. Residual stress measurements using the serial split-width technique indicated that the real residual stress was comparable to (or less than) the equivalent "residual stress," which has been used as a measure of structural perfection in web crystals in previous reports.

New dynamic and new static configurations were given preliminary evaluation in the laboratory, with results generally in agreement with the made predictions. Improved system temperature measurements were made leading to growth in closer agreement with the model predictions. Improved methods for controlling convective gas flow and oxide deposition were developed.

2. INTRODUCTION

Silicon dendritic web is a single-crystal silicon ribbon material which provides substantial advantages for the low-cost manufacture of solar cells. Growth from a melt of silicon without the use of constraining dies is a significant feature of the process, which results in an oriented single-crystal ribbon having excellent surface characteristics. In common with other more typical processes such as Czochralski growth, impurity rejection into the melt permits the use of less pure "solar grade" starting material without significantly affecting cell performance. A unique property of the dendritic web process is the growth of long ribbons of controllable width and thickness, which not only facilitates automation of subsequent processing into solar cells, but also results in high material utilization since cutting and polishing are not required.

On the present contract, three broad areas of work are emphasized:

1. The development of thermal stress models in order to understand the detailed parameters which generate buckling stresses, and the application of these models to the development of new low-stress design concepts.
2. Experiments to increase our understanding of the effects of various parameters on the web growth process and to complement and verify the results of the modeling effort.
3. The construction and utilization of an experimental web growth machine which contains in a single unit all the mechanical and electronic features developed previously so that experiments can be carried out under tightly controlled conditions.

The principal objective of this work has therefore been to expand our knowledge and understanding of both the theoretical and experimental aspects of the web growth process to provide a solid base

for substantial improvements in both area throughput and web crystal quality, and to develop the tools necessary to carry out this objective.

During this abbreviated reporting period, new dynamic and static growth configurations were developed and tested, the split-width technique was evaluated in terms of true residual stress in web crystals, and improved temperature measurements and oxide control techniques produced improvements in growth.

3. TECHNICAL PROGRESS

3.1 Modeling and Material Analysis

During the report period two types of design concepts were evaluated: (1) a vertical thermal element which not only modifies the temperature profile in the web but also changes the convective gas flow near the web, and (2) a thinner lid configuration in which the second lid is replaced by a hot cavity. The modeling results indicated that each of these concepts had potentially positive aspects. However, they also had potential difficulties and the actual worth of the designs will have to be determined by growth experiments.

Material evaluation was mainly directed toward determining the real residual stress distribution in web crystals using a serial split-width technique. The preliminary measurements indicated that the real residual stress in the sample edge was comparable to the equivalent "residual stress," which has been used as a measure of structural perfection in web crystals in previous reports.

3.1.1 New Growth System Designs

The first of the new design concepts to be evaluated was the use of a vertical radiation shield as the final element of the shield stack. This concept, which is shown schematically in Figure 1, has several interesting features. First, it permits a higher hot environment around the web than is possible with horizontal shields while still maintaining a reasonable view angle at the growth front. Secondly, it provides a means for modifying the gas flow above the lids and shields. Growth experience on the pre-pilot line at Westinghouse AESD suggests that both effects may be beneficial to crystal growth.

Dwg. 9357A09

Figure 1. Schematic representation of vertical thermal elements.

The effect of such "billboard" shields was modeled for two of our lowest stress designs, the J460 and the J483. In each case, the effective temperature of the vertical element was extrapolated from the assumed shield temperature distribution and the height of the element chosen to continue the clear view line of the basic configuration. The significant thermal stress results for these models are shown in Figures 2 to 5. The curves represent the delta x-stress distribution along a web crystal with the standard width of 2.7 cm. The delta x-stress parameter was chosen since the "far peak" at 3 to 6 centimeters from the growth front appears to be directly related to the propensity of the ribbon to buckle.

The first set of curves represents the results for the analysis of the J460 configuration. Figure 2 shows the delta x-stress distribution for the baseline configuration, while Figure 3 represents the configuration modified with vertical thermal elements. The peak value of delta x-stress is 195 Mdyn/cm^2 for the baseline case and 170 Mdyn/cm^2 for the configuration with an added "billboard." Although this is a modest reduction in stress, it indicates that the change is in the right direction and hence that the vertical thermal elements can indeed be used for thermal stress control. As might be anticipated, the stresses near the growth front are unchanged as is the growth speed.

Similar results were found for the modified J483 configuration. The original σ_x distribution is shown in Figure 4; the peak stress is 99 Mdyn/cm^2 at about 6.5 cm from the growth front. When the vertical thermal elements were added, the stress peak was reduced to about 77 Mdyn/cm^2 , and the whole distribution spread out as shown in Figure 5. The effect of the added elements clearly has been to smooth out the thermal transition at the top of the stack of horizontal shields. As with the model of the J460 configuration, the stress distribution near the growth front and the growth velocity are essentially unchanged.

As the stress peaks far from the growth front are reduced, the stresses near the growth front assume greater relative importance.

Figure 2. Delta x-stress for original J460 configuration.

2D SILICON STRIP CASE 9-65 -C

Figure 3. Delta x-stress for J460 configuration with vertical thermal elements.

Figure 4. Delta x-stress for original J483 configuration.

2D SILICON STRIP CASE 9-64 -C

Figure 5. Delta x-stress for J483 configuration with vertical thermal elements.

Understanding the thermal stresses in this region is complicated by a number of factors. First, the growth front and the ribbon edges are free boundaries, which means that the stresses normal to the boundary and shear stresses parallel to the boundary are zero irrespective of the temperature profile. These boundary conditions strongly influence the stress distribution for a distance along the ribbon about equal to the ribbon width.⁽¹⁾ Secondly, the ribbon is hottest at the growth front so that the heat losses are largest -- and rapidly changing -- resulting in a complicated distribution of (αT) , the "driver" for thermal stress. These two effects combine to complicate the prediction and control of the stress distribution near the growth front.

As an example of the complexity of stress effects near the growth front, we can consider the RE-1 and J460 configurations. The RE-1 is an early growth configuration and is shown schematically in Figure 6.⁽²⁾ Early stress modeling results predicted a strong dependence of the centerline y-stress on LIN as shown in Figure 7;⁽³⁾ recent analysis using our current temperature model confirmed these earlier results in all essential features. The J460 is a more recent growth configuration than the RE-1 and has a much smaller delta x-stress;⁽⁴⁾ however, the variation of the y-stress with the LIN parameter is much weaker as shown in Figure 8. What would be desirable is to combine the small delta x-stress of the J460 configuration with the small y-stress of the RE-1.

The essential characteristics of the two designs would seem to be the relatively thin lid in the RE-1 and the relatively tall shield stack in the J460. These two features were combined in the conceptual model shown in Figure 9. The J460 lid is shown in dashed outline; lid 2 is little more than a hot spacer. The results of modeling several variations of this scheme were somewhat disappointing. The delta x-stress distribution was similar to the J460 results, but the y-stress curves showed relatively large values at the growth front; e.g., 850 Mdyn/cm² compared to 550 Mdyn/cm² in the case of the baseline J460. This interface stress did show a marked variation with LIN, but not to

Figure 6. Schematic representation of RE-1 configuration.

Curve 714928-A

Figure 7. Centerline y-stress for RE-1 configuration with LIN as the parameter.

Curve 742148-A

Figure 8. Centerline y-stress for J460 configuration with LIN as the parameter.

Dwg. 9357A10

Figure 9. Conceptual combination of RE-1 and J460 configurations.

the extent exhibited by the RE-1. Clearly more work is necessary to control the thermal stresses near the growth front.

3.1.2 Material Analysis

During the reporting period, the work on the material analysis has been directed toward evaluating the true residual stress in the web ribbons as opposed to calculating an average bending moment stress. As discussed in the previous report,⁽⁵⁾ the residual stress numbers that we have been reporting are more accurately equivalent surface stresses which would result from bending a uniform thickness ribbon to the same curvature observed in the split width measurements.⁽⁶⁾ The purpose in the present work was to evaluate the true residual stress in the ribbon as a function of position across the web width. For the specific case that we measured, the real stress was actually smaller than the "residual stress" that would be calculated on an average basis.

The technique that we are applying is called the "serial split-width measurement" method since it relies on measurement of the separation between the two halves of a web strip split longitudinally down the middle. Strips are then removed from the outer edges of the sample and the measurement repeated on the remaining material. The average real stress in the small strips that have been removed can then be calculated from the changes in the curvature of the split.

The basis for the calculation is the bending moment associated with the residual stress distribution in the initial web crystal. Since residual stress appears to be essentially constant over long lengths of the web, the only non-zero stress component is σ_x , which may vary across the width of the ribbon (in fact it must vary across the width since its integral over the cross section must be zero). This stress distribution gives rise to a bending moment

$$M = \int_0^w y^2 \sigma_x dA \quad (1)$$

where w is the half width of the original (unsplit) web crystal. The integral of Equation 1 can be written

$$M = \int_0^{w-\Delta} y^2 \sigma_x dA + \int_{w-\Delta}^w y^2 \sigma_x dA \quad (2)$$

where $w-\Delta$ is the width of a narrow strip on the outer edge of the ribbon. The second integral on the right of Equation 2 is just the moment of the stress distribution in the narrow strip, while the first integral is the moment of the stress distribution in the balance of the web. The second integral can be approximated by

$$\int_{w-\Delta}^w y^2 \sigma_x dA = (w - \frac{\Delta}{2}) \overline{\sigma_x} \Delta A \quad (3)$$

where $\overline{\sigma_x}$ is the average x-stress in the narrow strip, ΔA is the cross-sectional area of the strip and $(w - \frac{\Delta}{2})$ is its average y-value, $\overline{y}$. If one could measure the moments of stress in the ribbon with and without the narrow strip, then one could obtain the average stress in the strip. These moments are related to the curvature of the strip by the relation

$$M = EIC \quad (4)$$

where E is Young's modulus (taken as 1.9×10^6 Mdyn/cm²), I is the area moment of inertia of the cross section, and C is the curvature (the coefficient a_2 in our split width analysis.⁽⁵⁾ Using Equation 3 and Equation 4 we thus have

$$\overline{\sigma_x} = \frac{E(I_1 C_1 - I_2 C_2)}{\overline{y} \Delta A}$$

where the subscripts 1 and 2 refer to measurements of the ribbon with and without the narrow strip.

A set of measurements was made on a crystal that had a reasonably large stress value from the average moment technique used previously (28 Mdyn/cm²). After the dendrites had been removed, the

sample was remeasured and then an additional 2.6 mm strip was removed and the sample again measured. The results are tabulated in Table 1. If the $\bar{\sigma}_x$ values are extrapolated to the sample edge, the resulting stress is only 19 Mdyn/cm². Considering that the dendrite area was included in the detailed computation while the average moment calculation assumes a flat ribbon, it would seem that the two values are in very good agreement and that our previous numbers were probably good measures of the residual stresses actually present in the web material.

Based on these results, our future plans would include verification with one or two more samples, but in general it would appear that a single split-width measurement is sufficient to characterize the general stress level in a web crystal.

Table 1
Results of Serial Split-Width Measurements on Sample J515-2.2

Case	w [cm]	I [cm ⁴]	C [cm ⁻¹]	ΔA [cm ²]	$\bar{y}$ [cm]	$\bar{\sigma}_x$ [Mdyn/cm ²]
1	1.279	5.06×10^{-3}	23.2×10^{-6}			
2	1.011	1.55×10^{-3}	5.65×10^{-6}	1.29×10^{-2}	1.15	14.0
3	.735	$.60 \times 10^{-3}$	-0.52×10^{-6}	4.97×10^{-3}	0.87	4.0

3.2 Experimental Web Growth

3.2.1 Introduction

During this reporting period, laboratory work concentrated on growth runs involving dynamic hardware leading to a new dynamic growth configuration, the RF443, and the preliminary evaluation of a new static configuration, the J517. In addition, improved system temperature measurements were made, suggesting some refinements to bring true temperatures into closer agreement with the model. Hardware modifications

developed in recent months for controlling the effects of convective gas flow were applicable to all the newer growth configurations, and led to improved growth in the J503 configuration.

3.2.2 Dynamic Growth Configurations

Having demonstrated the potential for substantial enhancement of growth velocity by the dynamic control of LIN, the position of the growth interface relative to the lid, the next step was to attempt to combine the dynamic capabilities with the width capabilities of low-stress lid and shield configurations. The first experiments relating to this objective were carried out with a modified J460 configuration, and although the expected enhancement in growth velocity occurred, considerable effort would be required to optimize the system for concurrent wide crystal growth. Meanwhile, the static low-stress J503 configuration was developed to the point where good growth could be achieved, and so it was adapted for use in a dynamic growth system. The new dynamic configuration, designated the J443, was tested experimentally and generated growth velocities of 2.1 cm/min with the lid/shield stack in the raised (melt down) position, increasing to 2.5 cm/min in the fully lowered position. This is to be compared with ~ 1.8 cm/min with the basic J503 configuration. However, like its predecessor, considerable effort would be required to generate the optimum temperature distributions for combining the enhanced growth velocity with wide web growth.

3.2.3 The J517 Configuration

A new static design, the J517, incorporating substantial changes in the lid configuration, was tested in the laboratory. The objective of this design was to modify the temperature distribution in the web near the growth interface and thereby enhance the growth velocity.

Two slightly different variations of the design were tested, differing only in the separation between the lids and first shield. Growth velocities at standard thickness showed only a small difference

between the two cases and were increased by the 10 to 15% predicted by the model over the standard J460 configuration. The stresses also appeared to be somewhat higher, as predicted by the model, although these have not been quantitatively evaluated. Some modifications in lid design and further experimental effort would be required to assess the trade offs and determine whether a significant increase in growth velocity could be maintained at acceptable stress levels.

3.2.4 Temperature Measurements

It has been routine to position thermocouples in the first and fourth top shields in all the growth runs. While the temperatures indicated by these thermocouples reproduced well for identically configured runs, we became suspicious that the immersion losses were larger than we thought, and therefore the actual temperatures might be significantly higher than indicated and higher than those used in the model calculation. We therefore modified the thermocouple placement such that the lead-in paths are located between the shields, minimizing immersion losses. The results, based on several runs, showed that the temperature of S1 was only about 10° higher than previous measurements, while S4 was over 40° higher. This result was checked by instrumenting S4 with two thermocouples, one positioned with the leads above the shield and one with the leads below the shield between S3 and S4.

In order to bring the true temperatures closer to the model, runs were made in the J460 configuration with S3 and S4 slitted around the periphery to reduce r.f. coupling. Web crystals were grown at different thicknesses and the width at the initiation of buckling measured. The results were in excellent agreement with the predictions of the model up to 4 cm, the maximum tested.

3.2.5 Control of Convective Gas Flow

Convective gas flow in the web growth furnace is complex and not fully understood. In terms of the effects on web growth, the most

important aspect of the flow patterns is the distribution of the oxide generated by the reaction of the molten silicon with the quartz crucible. Excessive deposition in the furnace chimney, web guides, or on the top shields in the growth region can lead to problems such as oxide falling into the melt during growth, particularly during extended, multi-day runs. Furthermore, the convective gas flow and the associated oxide deposition patterns can change significantly with changes in growth configuration.

Even without full understanding of the mechanisms, we have developed empirically a number of techniques for controlling the oxide deposition so that deposition in sensitive areas is minimized. For example, we observed that oxide deposition at the base of the chimney increased as the height of the lid and shield stack increased with the newer growth configurations. This problem was controlled by raising the chimney with a spacer block on the furnace cover.

For some other examples, an oxide deposition on the web guides was minimized by changing the design of the spacers positioned between the top shields. Some time ago, oxide deposition on the shield feed holes was eliminated by redesign of the hole configuration in the top shields.

In summary, we have developed empirically means to alter the convective gas flow patterns such that the oxide largely deposits where it is not harmful to growth. These may be modified as needed for future growth configuration designs.

4. CONCLUSIONS

The routinely used split-width technique for measuring residual stresses was evaluated by using the serial split-width technique to determine the stress distribution across the web crystal. The results indicated that the true stress was comparable to or less than the residual stress values generated by the conventional single split measurement.

New growth configurations tested in the laboratory gave results in general agreement with the model predictions. However, the results though preliminary suggest that some design modifications will be needed to fully evaluate the capabilities of the basic designs.

Modifying top shield temperatures to be more consistent with the model led to excellent agreement with the buckling model results for the J460 design up to the 4 cm widths tested. Hardware modifications, in some cases relatively minor, can have significant influence on convective gas flow and thus permit the distribution of oxide deposition to be controlled.

5. PLANS AND FUTURE WORK

A new dynamic growth configuration will be modeled, fabricated, and tested in the laboratory to assess its potential for growth velocity enhancement. A manual of operating procedures will be prepared for the N-furnace. The design drawing package will be updated to include dynamic hardware.

6. NEW TECHNOLOGY

No new technology is reportable during this period.

7. REFERENCES

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2. C. S. Duncan, et al., "Silicon Web Process Development," Annual Report, April 1978 to April 1979, DOE/JPL-954654-79/2, p. 16.
3. Ibid., p. 154.
4. C. S. Duncan et al., "Advanced Dendritic Web Growth Development," Annual Report, October 23, 1981 to October 23, 1982, DOE/JPL-955843/83/8, p. 40.
5. C. S. Duncan et al., "Advanced Dendritic Web Growth Development," Annual Report, October 23, 1982 to October 22, 1983 DOE/JPL-955843/84/12, p. 30.
6. Ref. 5, Appendix 1.

8. ACKNOWLEDGEMENTS

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9. PROGRAM COSTS

9.1 Updated Program Plan

- 9.1.1 Program Labor Summary (see pg. 27)
- 9.1.2 Program Cost Summary (see pg. 28)
- 9.1.3 Milestone Chart (see pg. 29)

9.2 Man-Hours and Costs

9.2.1	<u>Man-Hours</u>
Previous	41,125
This Quarter	2,421
Cumulative	43,546

9.2.2	<u>Costs</u>
Previous	\$1,991,656
This Quarter	141,814
Cumulative	\$2,133,470

Curve 742604-8

PROGRAM LABOR SUMMARY
JPL CONTRACT 955843, MOD. 12

Curve 742605-8

PROGRAM COST SUMMARY JPL CONTRACT 955843, MOD. 12

Doc. 5400C58

FSA PROJECT
LARGE AREA SILICON SHEET
ADVANCED DENDRITIC WEB GROWTH DEVELOPMENT
MILESTONE CHART - JPL CONTRACT 955843, MOD. 12