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SILICON WEB PROCESS DEVELOPMENT

Low Cost Solar Array Project, Large Area Silicon Sheet Task
Quarterly Report, July 1–September 30, 1978

By
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Solar Energy

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LOW COST SOLAR ARRAY PROJECT
Large Area Silicon Sheet Task

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ABSTRACT

A manually operated system for continuous melt replenishment was completed and installed in the RE web growth facility late in this reporting period. Initial results are positive though incomplete. Polysilicon pellets were fed for comparatively short periods, to 14 minutes, while web was growing without any disturbance from the pellet feed. A bench model of a manually-controlled mechanical pellet feeder was developed for later inclusion in the melt replenishment system.

An after-heater with adjustable temperature and adjustable temperature gradient was installed in the J web growth facility for the purpose of controlling the vertical temperature gradient and the thermal stress generated in the growing web. The initial operation disclosed that the range of temperatures was somewhat less than intended and minor modifications have been made but not yet evaluated.

The W web growth facility has performed well with respect to width control. Two problems have persisted and are undergoing developmental improvement: excessive deposits of oxide on the web, lid and heat shields and, secondly, objectionably high stress in the web.

Computer models of temperature profile and stress are being used to support the development of lower stress in web grown from the W facility and the J facility which includes the afterheater system for vertical temperature gradient control. In addition, actual stress measurements in web grown are routinely made in order to evaluate results.

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1.0 INTRODUCTION

The overall intent of this program is to further develop the dendritic web crystal growth process to the extent that it satisfies the economic goals of the Large Area Silicon Sheet Task of the JPL Low-Cost Solar Array Project.

The ability of the process to produce crystals for high efficiency solar cells, 15.5% AM-1 or higher, is well known and has been demonstrated in pilot production and in this program. The prior state of development of the process did not, however, have sufficient throughput to satisfy the cost goals of the LSA Project.

Consequently, a key goal of this program is to increase the throughput of the process in terms of greater width and speed as required to reach an area rate of growth of 25 square centimeters per minute. Another goal is to produce lengths greater than ten meters and thicknesses within the range of 100 to 200 microns.

Phase I of this program, covering the first year, was completed April 19, 1978. An economic analysis prepared near the conclusion of Phase I indicated that, with appropriate continued development, the silicon web process presented the opportunity to equal or better the JPL 1986 cost goal for solar cell wafers. Considering the status of development and the cost sensitivities as identified by economic analysis, development emphasis and tasks for Phase II were determined.

The goals for Phase II are: $25 \text{ cm}^2/\text{minute}$ area rate of growth, greater than 10 meters length, less than 10^4 cm^{-2} dislocation density and 100-200 μm thickness. This development is being carried out by diversified personnel selected to serve the dual need of continued throughput development combined with process and equipment engineering preparatory to future pilot production. The throughput development personnel are a

continuation of the Phase I activity. The process and equipment engineering activity began with Phase II of this program and is staffed by personnel experienced in the engineering oriented functions. The engineering activity constitutes approximately thirty percent to the total Phase II effort.

During Phase II a third growth facility has been added to the two facilities which were in use at the end of Phase I. The new facility was modified from existing equipment expressly for this program, will be operated solely by engineering personnel.

Dynamic thermal trimming has been built and installed in one of the web growth facilities and experimental operation has begun. Its goal is to minimize stress in the growing web such as to allow greater width and length of growth without deformation.

A manually operated replenishment system has been built and installed in another of the web growth facilities and experimental operation has begun. The goal of this task is to provide for longer periods of growth as ultimately required for fully automatic growth. A constantly maintained melt level, made possible by melt replenishment, has the added advantage of contributing to constant thermal conditions and uniform growth.

Development and optimization of lid geometry is being carried out as a continuation of Phase I and has been expanded as required for the dynamic thermal trimming and melt replenishment tasks.

Thermal modeling has also been continued and expanded for use with the dynamic thermal trimming and melt replenishment tasks.

Evaluation of the effect of seeding variations and structural characterization of web crystals is being conducted more intensively than during Phase I.

Solar cells are being prepared from silicon web by routine standardized fabrication techniques as a means for evaluating the quality of web made by various developmental methods.

Finally, the economic analysis of the process will be updated as required to reflect cost changes indicated by continuing process development.

Successful completion of these tasks is expected to satisfy the Phase II wafer cost goals and in so doing achieve a throughput rate essential to the overall JPL 1986 cost goal for solar modules.

2.0 TECHNICAL DISCUSSION

2.1 Web Growth Experience

2.1.1 RE and J. Web Growth Facilities

2.1.1.1 Introduction

During this quarter, a total of 66 experimental web growth runs were made, 34 in the RE facility and 32 in the J. Details are summarized in Appendix, 6.1. A manual melt replenishment system¹ has been installed on the RE facility. A number of tests were carried out in order to demonstrate feed during web growth using pellet feed stocks and to check out potential problems which might need consideration in the design of an automated long run duration melt replenishment system. No attempts have yet been made to maintain melt level for a long period of time. The results of these preliminary tests are discussed in section 2.1.1.2.

An after heater system¹ for trimming the vertical temperature gradients in the web was constructed. It was designed for easy installation and removal in the J facility between runs, via one of the access ports in the furnace enclosure. Several growth runs were made using the after heater for preliminary design evaluation. The results are discussed in section 2.1.1.3.

There has been an increasing problem of late with the appearance of small particles of free floating "ice" in the melt during web growth, causing premature degeneration of web quality or pullout. This phenomenon was unexpected, because it occurred with susceptor lids which had previously yielded good results, and when the slot region remained oxide free. In the past, harmful ice formation would tend to occur only if oxide which had nucleated and built up on the edge of the slots in the lid or top shields fell into the melts. It was observed that the lower surface of these lids tended to accumulate some oxide which could have

spalled off as small particles during web growth. The phenomena was associated with lids that had been used and cleaned and polished many times - not with "new" lids.

The initial reaction to this phenomena was to attempt to do a better cleaning job, since we had substantial experience that in the slot a smooth surface does not provide nucleation sites for oxide. The situation worsened however and, accordingly, we reversed the logic and lightly sandblasted the bottom lid surface. On the basis of the first three runs per lid, after a single "roughening", not only was spalling eliminated, but the accumulation of any significant oxide on the lower lid surface was foiled. Although we cannot yet fully explain these results, the revised procedure apparently provides a satisfactory solution to the problem.

2.1.1.2 Manual Melt Replenishment System

The functional parts of the manual feed system¹ are (1) a chamber for storing a supply of silicon pellets, (2) a manipulator mounted on top of the storage chamber which enables the operator to drop pellets into a funnel topped feed tube, and (3) a feed tube assembly. The feed tube assembly incorporates a valve so that the storage chamber may be isolated from the furnace growth chamber for reloading.

A susceptor lid and set of top shields were modified to allow penetration of a quartz feed tube at a position near one end of the crucible. A quartz barrier was positioned 16 mm from one end of the crucible with a nominal 1.6 mm spacing from the crucible bottom so as to provide a "leaky" replenishment compartment. The purpose of the barrier is to prevent unmelted feed material from floating into the growth region of the melt and interfering with web growth. Feed stock consisted of 3 mm polysilicon cubes. The size was selected as convenient for manual feeding at a reasonable rate for evaluation purposes, and should not be construed as ideal for a practical automated melt replenishment system.

During the initial experiment with the feed system, the bottom of the feed tube became clogged with a thin, firm layer of oxide rather quickly, before any feeding could be accomplished. In order to prevent this oxide buildup, an argon flow system incorporating a flow meter was installed so that a measured flow of argon could be maintained down the feed tube. Tests with flow rates of 500 to 25 cm³/min indicated that a rate of about 100 cm³/min. was adequate to prevent clogging of the feed tube.

Several experiments were carried out in which silicon pellets were fed into the crucible while web was growing; for periods of up to 14 minutes at frequencies of 3 to 4 pellets per minute. In three runs, no disturbance of the melt was noted when pellets hit the melt surface (essentially a free fall for over 30 cm). In one run, a slight mechanical disturbance was observed when each pellet entered the melt, but, the magnitude was too small to disturb the web growth. In the former case, post run examination of the crucible revealed that all of the molten silicon had moved into the growth compartment of the crucible, leaving the feed compartment side of the barrier dry, or with a few droplets representing the last few pellets introduced. In the latter case, the melt was distributed between the feed and growth compartments of the crucibles. Also in the latter case, the gap between the barrier and the bottom of the crucible was larger than in the former. This phenomenon is apparently related to the surface tension and wetting characteristics of silicon on quartz. The need for further study of barrier geometries in order to maintain reproducible behavior is clearly indicated.

It must be noted that the feeding experiments carried out thus far are not entirely conclusive. They were performed during the problem period of the floating "ice" particles discussed in the previous sections. Such "ice" sometimes occurred during a feeding experiment, but it also occurred without feeding and even in runs without the feed system in place. Thus, while there is no reason at this time to believe that feeding pellets into an suitably compartmented crucible contributes to any web growth problems, further experiments without the above complication are needed to yield an unequivocal conclusion.

2.1.1.3 Experimental Feeder for Melt Replenishment

Maintaining a constant melt level requires some form of mechanized melt replenishment. For various reasons (previously described), it has been decided that the melt can best be fed using spherical polycrystalline silicon pellets of approximately 2 to 3 mm diameter. In order to maintain a constant melt level, some form of mechanized feeding of these pellets is required. For this phase of the program, the feed rate will be controlled at approximately the same rate that the melt is being depleted by the growing web. This will be done in an "open loop" control with no melt level sensing or feedback. Instead, the approximate withdrawal rate will be calculated on the basis of width, speed and thickness, and the feed rate will be adjusted appropriately to maintain a near constant melt level.

A list of requirements for the mechanized feeder has been identified:

- (1) Must be capable of feeding both cubes and spheres
(2.4 mm cubes will be used during initial experiments).
- (2) Must be capable of feeding a single pellet on command.
- (3) Must be capable of feeding pellets at a constant rate
of up to 30 per minute.
- (4) Must not contaminate pellets.
- (5) All parts must be suitable for vacuum (no out-gassing, etc.).
- (6) All parts must be suitable for operation in an argon
atmosphere.
- (7) Mechanism must not induce vibrations into the melt.
- (8) Must not abrade the pellets.
- (9) Must be capable of being reloaded without disturbing
web growth.

A literature search was conducted a number of concepts were identified that could potentially lead to a satisfactory feeder. Also, a number of vendors, particularly in the pharmaceutical area, were contacted in regard to dispensing pills and tablets. As a result of this investigation, a rather simple concept was selected which appears to meet all of the above requirements.

The mechanized feeder concept, as shown in the bench model Figure 1, consists of a slowly rotating dish called a "separator." It is presently made of highly polished stainless steel and is turned at the same rate as the pellets are fed. Its job is to separate one pellet from the load of pellets in the dish. The dish is inclined at 35 degrees from the horizontal so that the pellets tend to flow, not tumble, to the lower side. In the bottom of the dish near the vertical wall is a 4.2 mm hole. The bottom of the dish is 2.4 mm thick. The hole diameter is just slightly larger than the maximum pellet dimension (the diagonal of 2.4 mm cube is 4.15 mm). With the dimensions chosen, only one pellet can fit into the hole so that as the dish turns and a pellet falls into the hole, the pellet is separated from the mass of pellets in the dish.

The bottom of the hole in the dish is covered with a spring loaded gate, actuated by a fixed cam which released the captured pellet once every revolution of the dish. On the present model, the maximum rate is 10 pellets/minute. To double the rate a second hole can be added, etc. The release point is determined by the location of the cam. The present concept calls for the pellet to be released or dropped into a small funnel which leads through a tube directly into the melt.

The mechanized feeder can readily be added to the present manually operated melt replenishment system of the RE web growth facility. To do so will require an appropriate mounting and a hermetic enclosure for the separator dish sub-assembly.

Figure 1 Bench Model of Mechanized Polysilicon Pellet Feeder

2.1.1.4 Vertical Gradient Thermal Trimming

The after-heater system¹ was designed to provide thermal trimming of the vertical temperature gradient in the growing web in the region approximately 1 to 10 cm above the susceptor lid. Thermocouples mounted in all four heater blocks allow temperature measurements to be made during operation. Heater power input can be adjusted so that the front-back heater pairs can be matched to within about 1°C. The thermocouple outputs are fed into a data logger so that temperatures can be monitored continuously. The maximum ΔT , from bottom to top of the heater assembly, i.e. full power on the lower end zero power on the upper heaters, is about 350°C, or an average gradient of 70°C/cm. With the susceptor at operating temperature, and the bottom of the heater assembly 2.5 cm above the lid, the maximum and minimum temperatures at the bottom heaters are approximately 930°C and 780°C respectively. This represents a rather limited range. In particular, the ability to operate at lower temperatures would be desirable. Some radiation shielding to reduce heat transfer from the top of the susceptor lids may help. It may further be desirable to add active cooling in order to expand the temperature range available to test purposes.

During the initial test run, the thin gradient plates distorted such that the front-back spacing varied substantially over the gradient area. Some changes in material and manner of fabrication are expected to alleviate this problem.

The initial web growth experiments with the afterheater assembly have been quite inconclusive. We have not yet grown web of sufficient width in combination with an afterheater to evaluate the effect of the afterheater on stress in the web. In its present configuration with present lid designs, convective gas flow is sufficiently perturbed so as to cause excessive oxide buildup on top shields, which in turn has a deleterious effect on web growth. On the positive side, this initial experience has pointed out some directions which will be followed in future design modification.

2.1.2 W. Web Growth Facility

In this quarter the W furnace was operated on an essentially daily basis. The objectives for this quarter were to reduce the stress levels in the silicon web and to make the growth of crystals more routine. Daily operation of the furnace is one step in making the growth of web more routine.

At the beginning of the quarter the lid being used had a long dogbone-shaped slot with a full bevel and was used in combination with only one shield. The melts initially weighed in the range of 100 to 110 grams. One of the initial changes was the increase in the amount of silicon used. Instead of a range of 100 to 110 grams, the nominal silicon weight was increased to 120 grams. When stress measurements were made on lengths of web pulled while the melt level was high, the stresses were found to be reduced nearly by half. This points out another reason for the importance of melt replenishment in addition to its primary function of providing extended growth time.

A major change was the length of the lid's growth slot from a long dogbone shape to a short dogbone. The reason for this change was to achieve reproducible growth of long web meeting the intermediate width goal of 2.1 cm. The short dogbone lid had a second shield added on run W-39. It was with this lid geometry that the first web over 300 cm was grown from the W furnace; this web had the least degree of stress of any web from the W furnace to date. Figure 2 shows a 17 foot length of silicon web being removed from the storage reel.

Since oxide had nearly closed the ends of the dogbone on the run producing low stressed web the next lid used only a straight slot without dogbones. Since that time varying bevel depths have been used in a study of the bevel/stress relationship.

With the slotted lids long growth of web is becoming more common and increasingly long crystals are being pulled. Details of the W facility experimental web growth runs are summarized in the Appendix, 6.1.

Figure 2 A 17 foot length of silicon web being removed from the W web growth facility.

2.2 Material Characterization

The dendritic web material grown in the program has been characterized in a number of ways. The dimensional characteristics of the material are given in Appendix 6. along with the run data. Other characterization data such as device properties, residual stress data, and some structural studies are reported in this section.

2.2.1 Solar Cell Properties

The most operational evaluation of the dendritic web material with regard to the overall program goals lies in the quality of solar cells produced from it. Table 1 gives the performance data for cells processed on a number of dendritic web crystals during the report period; generally each entry represents the average data of from 2 to 6 cells processed from the same crystal. The details of the test cell design and the processing sequence are given in the Annual Report of Contract DOE/JPL 954654 (April 20, 1977-April 19, 1978). Usually the web material is subjected only to a thorough surface cleaning before processing. In some instances, however, about 10 μm of material are chemically polished from each surface before processing and this has been noted in the remarks column. In some instances this treatment improves cell performance greatly (e.g. R238-14, R238-1.5) while in other instances the performance is slightly degraded (e.g. W37-2.4). The reasons for this difference in reaction to surface treatment are not fully understood but are thought to be related to possible surface contamination during growth.

The data has been examined to see if any differences can be found which can be attributed to the system geometry. No obvious relationship could be found between cell performance and growth geometry, however there did appear to be some dependence of cell performance on the growth facility. If the average efficiency of recently grown and processed web crystals is compared, one obtains the following results (n = number of crystals in sample), in Table 2.

TABLE 1 WEB SOLAR CELL DATA

CRYSTAL	RUN	I_{sc} mA	V_{OC} Volt	FF	η_o %	η_{AR} %	T_{OCD} μS	REMARKS
R228-3.1	WQ5	21.1	.548	.726	8.9	12.7	5.2	
R229-2.2	WQ6	22.0	.563	.749	10.1	14.4	41.0	
R230-1.3	WQ5	22.0	.572	.736	9.8	14.0	11.2	
R230-2.4	WQ5	21.2	.561	.731	9.2	13.1	5.9	
R235-3.4	WQ7	19.4	.504	.731	7.6	10.9	1.0	
R235-3.4	WQ8	21.6	.541	.744	9.2	13.2	3.4	CHEM POLISHED
R238-1.4	WQ8	22.4	.572	.754	10.2	14.6	18.0	CHEM POLISHED
R238-1.5	WQ7	18.0	.470	.708	6.3	9.0	1.1	
RE3-6.3	WQ5	22.2	.560	.741	9.7	13.9	17.4	
RE11-4.3	WQ4	21.6	.529	.684	8.3	11.9	6.9	
RE12-3.2	WQ6	22.7	.563	.749	10.1	14.4	41.0	
RE14-2.3	WQ4	21.4	.509	.661	7.6	10.9	4.4	
RE15-3.4	WQ4	20.6	.504	.700	7.7	11.0	3.3	
RE18-1.4	WQ4	20.9	.543	.726	8.7	12.4	4.9	
RE18-3.3	WQ4	19.4	.526	.740	8.0	11.4	0.9	
RE23-3.2	WQ5	21.1	.513	.719	8.2	11.7	7.0	
RE24-1.3	WQ6	23.4	.561	.727	10.1	14.4	43.9	
RE25-2.2	WQ6	23.6	.553	.743	10.3	14.7	25.0	
RE25-3.1	WQ8	23.2	.569	.752	10.5	15.0	31.9	
RE26-3.3	WQ6	22.8	.564	.732	10.0	14.3	31.4	
RE26-5.2	WQ6	22.1	.545	.737	9.4	13.4	24.7	
RE28-5.2	WQ6	22.8	.567	.749	10.2	14.6	36.1	
RE29-35	WQ7	21.6	.538	.724	8.9	12.7	12.0	
RE30-1.4	WQ7	22.4	.543	.746	9.6	13.7	23.0	
RE30-2.2	WQ7	21.6	.541	.737	9.1	13.0	14.6	
RE32-4.1	WQ8	22.6	.560	.745	10.0	14.3	33.8	
RE32-5.1	WQ8	22.6	.570	.751	10.2	14.6	23.7	
RE33-1.3	WQ8	22.6	.557	.740	9.8	14.0	35.4	
RE33-3.3	WQ8	22.1	.553	.734	9.5	13.6	21.5	
RE33-5.1	WQ8	22.3	.564	.748	10.0	14.3	21.1	
RE34-6.3	WQ8	22.8	.565	.748	10.2	14.6	22.8	

TABLE 1 WEB SOLAR CELL DATA (Cont.)

CRYSTAL	RUN	I_{sc} mA	V_{OC} Volt	FF	η_o %	η_{AR} %	τ_{OCD} μs	REMARKS
J24-2.2	WQ5	20.3	.518	.704	7.8	11.2	2.1	
J31-3.1	WQ5	20.7	.526	.718	8.3	11.9	5.5	
J34-2.5	WQ5	21.8	.489	.690	7.8	11.2	4.1	
2.4	WQ6	21.8	.535	.724	8.6	12.3	8.0	
J49-1.2	WQ5	20.1	.485	.680	7.0	10.0	1.5	
J53-2.1	WQ8	22.6	.512	.709	8.7	12.4	7.1	
J53-4.4	WQ8	21.9	.516	.714	8.5	12.1	3.9	
J55-2.4	WQ7	21.9	.535	.721	8.9	12.7	10.4	
J55-3.1	WQ7	21.1	.514	.713	8.2	11.7	5.2	
J57-1.2	WQ7	22.3	.546	.728	9.4	13.4	23.7	
J57-2.2	WQ7	21.7	.547	.726	9.1	13.0	17.6	
J57-3.3	WQ7	21.3	.549	.737	9.1	13.0	14.3	
W13-1.4	WQ4	20.5	.515	.711	7.9	11.3	2.0	
W19-1.4	WQ5	21.6	.539	.742	9.1	13.0	10.9	
W22-5.5	WQ5	22.2	.540	.749	9.5	13.6	10.9	
W26-2	WQ5	21.7	.543	.746	9.3	13.3	8.0	
W27-5	WQ5	22.1	.539	.751	9.5	13.6	16.3	
W37-2.4	WQ8	22.6	.548	.743	9.7	13.9	27.3	
W37-2.4	WQ8	21.6	.539	.728	8.7	11.4	7.6	CHEM POLISHED
W41-1.8	WQ8	22.6	.562	.749	10.0	14.3	22.4	CHEM POLISHED
W41-1.8	WQ7	21.1	.562	.749	9.4	13.4	24.4	
W41-1.12	WQ7	20.8	.559	.745	9.2	13.1	18.2	
W43-1.4	WQ8	22.0	.542	.741	9.4	13.4	14.1	CHEM POLISHED

REMARKS :

$$A = 1.032 \text{ cm}^2$$

AM1 Illumination at 91.60 mw/cm^2 η_o = Efficiency without AR coating η_{AR} = Anticipated efficiency with AR coating

TABLE 2

Material	η_{AR}
RE Crystals (n = 10)	13.99 $\pm$.73
J Crystals (n = 7)	12.64 $\pm$.59
W Crystals (n = 5)	13.64 $\pm$.44

All of the J crystals were grown from the same lid-susceptor configuration as J53. The RE crystals represent two different geometries, however five crystals were grown from the same configuration as the J crystals. The W crystals were grown from a different configuration altogether. It would appear that for some reason, as yet unknown, the furnace itself may have an important influence on the quality of the devices. For example, there have been occasional problems with vacuum leaks in the J furnace. This effect is now under investigation.

2.2.2 Stress Measurements

During the report period, residual stress in a number of crystals was measured by the split width technique. Data for material grown in the J and RE furnaces was consistent with earlier measurements; crystals grown from the long, beveled slots had small residual stress, very nearby at the detection limit of about 10^7 Pa. As before, even crystals having low residual stress levels would exhibit deformation difficulties during growth.

A somewhat different state of affairs occurred with material grown in the W furnace which utilizes a round susceptor very similar to the one used in the R furnace configuration. A number of crystals grown from unbeveled slots had relatively large residual stress ($\sigma/w^2 \sim 6$ Pa/cm²) as expected. Beveling the slots reduced the stress to $\sigma/w^2 \sim 4$ Pa/cm² which is still about an order of magnitude larger than a similar profile would give in one of the elongated susceptor systems. The crystals, of course, had a strong tendency to curve. The reasons for this behaviour are not clear, but there is some suspicion that the lateral temperature profile might play some role.

2.3 Analysis of Thermal Stress Generation

2.3.1 Introduction

Part of the effort to reduce web deformation is directed toward understanding the nature and origin of thermal stresses generated in a growing web by the non-linearity of the vertical temperature distribution. There seems to be ample evidence from both the dendritic web program and from other sheet growth programs, such as the EFG and RTR studies, that under some circumstances plastic flow can occur in growing ribbon crystals. When these crystals are cooled, the resulting residual stresses can cause deformation of the crystal and in extreme cases spontaneous fracture. In dendritic web growth, the deformation of the growing crystal is the most serious problem since it can lead to degradation of the single crystal character of the ribbon as well as making growth difficult.

It has been found that in dendritic web growth it is possible to drastically reduce the residual stress in the ribbons by the proper design of the vertical profile of the slot in the crucible cover.² Although crystals grown from such configurations have low residual stress, they still deform during growth, albeit at greater width than those crystals with higher residual stresses. This observation has led to the hypothesis that the difficulty may arise from thermal stresses in cooler regions of the crystal away from the growth front where elastic rather than plastic deformation is the dominant result. Following this general direction, the problem has been attacked experimentally by including an afterheater in the growth system as discussed elsewhere in this report; the present section is concerned with the development of a model for the thermal stresses to be used for guidance in the experiments.

2.3.2 Temperature Profile Model

The existing model for the vertical temperature profile in the web crystal was expanded to include an afterheater and a 45° bevel on the slot. The geometry of the model is shown in Figure 3 which indicates the extensive parametric variation which is possible. As in the earlier version, all heat transfer is assumed to be radiative and the computation code accounts for the changing view factors as a function of position along the length of the crystal. The basic mathematics of the analysis

is discussed in detail on Appendix 6.5 of Ref. 2. As a practical matter, the computations are now being carried out using double precision arithmetic permitting a longer length of crystal to be included in the model before matching to an analytical solution.

Figure 4 shows some temperature profiles calculated for the afterheater geometry initially installed in the J-Furnace. The positions of the lid and afterheater assembly relative to the temperature profiles are indicated in the figure. The different curves represent different afterheater temperatures (TAS) which is assumed constant over the length of the heater. It is obvious that the heater has a strong effect after the first centimeter or so, however the temperature profile near the growth interface is essentially unaffected; the calculated partial growth velocities due to the heat loss from the crystal are within one percent for the three cases.

2.3.3 Stress Modeling

The temperature distributions calculated by the thermal model discussed in the previous section can be used as input data for a finite element model which evaluates the resulting thermally generated stresses in the ribbon. The model is extremely simple: an initially rectangular strip, representing half of the crystal, which is constrained only against rotation. The strip is then divided into an initially rectangular grid of 1 mm period along its length and 8 divisions across its width (which may be varied). The desired temperature distribution is then imposed on the strip and the resulting stress field calculated using the WECAN code. The program output generates a complete stress field analysis: σ_{zz} , σ_{yy} , σ_{xy} , principal stresses, and stress intensity. For the present, however, we will limit the discussion to the σ_{zz} field since most of the observed deformations in the dendritic web can be attributed to that component.

Figure 3 Model for Thermal Analysis

Figure 4 Web Temperature Profiles

In order to perform any quantitative calculations of thermally generated stress, three parameters must be known: Young's Modulus, E ; Poisson Ratio, σ ; and the thermal expansivity α . Although there is not a great deal of information available, some data can be developed for all these parameters. Young's Modulus and Poisson's Ratio can be calculated from the elastic moduli which were measured as a function of temperature by Burenkov and Nikanorov³. For the present purposes the calculations have been simplified by assuming that the material is elastically isotropic and the numerical value of $E = E_{111} = 1.9 \times 10^{12}$ dynes/cm²; the corresponding value for the Poisson Ratio is $\sigma = 0.20$. The temperature dependence for these quantities is sufficiently small that it may be neglected in the high temperature regime of interest.

Initially, the thermal expansion coefficient was taken from the work of Duta⁽⁴⁾ who published a quadratic formula which, when converted to Kelvin temperature, was

$$\alpha = \frac{1}{\ell_0} \frac{d\ell}{dT} = (2.73 \times 10^{-6} + 4.209 \times 10^{-10}T + 2.057 \times 10^{-12}T^2)K^{-1}. \quad (1)$$

Thus at 1500°K, $\alpha = 7.99 \times 10^{-6} K^{-1}$. The expression, Eq. 1, was used in the stress calculations presented in this report. Very recently other data on the lattice constant of Si at high temperature was discovered. R.O.A. Hall⁽⁵⁾ published data which when converted to expansivity resulted in a formula

$$\alpha = \frac{1}{\ell} \frac{d\ell}{dT} = \frac{d(\ln \ell)}{dT} = (2.552 \times 10^{-6} + 1.953 \times 10^{-9}T - 9.03 \times 10^{-15}T^2)K^{-1} \quad (2)$$

which gives $\alpha = 5.46 \times 10^{-6} K^{-1}$ at 1500°K. There is some preference for the latter expression since it leads to excellent agreement with Logan and Bond's⁽⁶⁾ independently determined value of 2.2861 for the density of solid silicon at the melting temperature whereas Duta's value does not.

One of first checks on the stress program was to evaluate the stress field resulting from a linear temperature profile with temperature independent material constants. As would be expected, the ribbon was essentially stress free; some very small stress values were in fact

calculated as a result of a finite size of the elements. A more interesting result occurred when a linear temperature profile was evaluated in combination with a temperature dependent coefficient of expansion: a stress field developed which had a maximum stress of almost 7×10^8 dynes/cm² or about 20% of the stresses observed with the non-linear temperature profiles run later. Considering the uncertainty associated with the expansivity this result should not be given too much importance, however it does indicate that the results of the stress modeling so far have more qualitative than quantitative value.

The most interesting results, in so far as giving direction for afterheater experiments, were stress calculations based on the three temperature profiles given in Figure 4 in the preceeding section. The three cases can be classified as hot, warm and cold afterheaters. One generalization can be made for all three cases, namely that the maximum stress difference, $\sigma_{zz}(\text{edge}) - \sigma_{zz}(\text{axis})$, occurs above the top surface of the susceptor lid where the web is moderately cool, eg $< 900^\circ\text{C}$, and that the edge of the crystal is in compression relative to the axis. The variation of this stress difference along the length of the crystal is illustrated for the case of the "cool" afterheater in Figure 5. The "warm" and "hot" afterheaters gave qualitatively similar results with some variation in the magnitude and position of the stress maximum. The "hot" afterheater had the largest stress maximum and the "cool" afterheater had the smallest.

In Figure 5 the second derivative of the temperature distribution for the "cool" afterheater is plotted in addition to the stress distribution. It can be seen that the two quantities are related, however other factors are involved, especially near the interface where the second derivative is changing rapidly. It should also be noted that the stress distribution across the ribbon follows the expected quadratic dependence far from the interface, however does not do so near the stress maximum. In fact, the maximum stress difference is more nearly linear with ribbon width.

Figure 5 Stress Profile

The temperature-stress modeling efforts to date show that a variety of temperature profiles can be achieved by the use of thermal trimmers or afterheaters. These profiles can then be used to generate the thermal stress field in the crystal. Because of the complicated relation between the thermal stress fields and the actual deformation of the crystal, it is somewhat uncertain just what actual stress levels can be tolerated. Therefore further design efforts will be directed to deriving system configurations which will minimize all thermal stresses.

2.4 Structural Studies

Various defects such as twin plane degeneration and lineage boundaries have been observed in dendritic web crystals and are thought to degrade solar cell performance and also may enhance the breakage of material during fabrication. Many growth problems, such as crystal deformation and degradation of the single crystal nature of the web are also manifested as observable structural defects. The present studies are an attempt to define the nature and source of some defects which are readily visible on the surface of dendritic web and relate them to specific difficulties in the growth process.

Surface lines of different types have frequently been observed on web surfaces. A variety of these different surface lines on fragments of web are shown in Figures 6 through 11. In the micrographs 6-9, some distinct vertical lines are visible on the surface of the crystals. These lines are commonly observed to develop during the early stages of degeneration of the web structure. There appear to be two different sources for the formation of these surface lines: (1) overthinning of the web after seeding, and (2) stress induced deformation of the web. These sources have been discussed in the Annual Report of this project.²

Micrographs of these different fault lines reveal slightly different microstructures. Some of these defect lines appear to be grain boundaries, while others seem to be twin related. These twin related defects may be caused by overthinning of the web or may represent the early stages of twin plane outcropping.² Another possibility is that these twins are deformation induced and are related to the high residual stresses in some crystals.

Figure 12 is a micrograph of the fault lines in Figure 6. These lines have the appearance of low angle grain boundaries formed by stress induced slip and dislocation pile-up which creates a lineage boundary. The line in Figure 13 is a micrograph of the line in Figure 7. This line also has the appearance of a low angle grain boundary. Dislocation interaction also appears to have been important in the formation of the line in Figure 8 as can be seen from the micrographs, Figures 14 and 15, which show the surface before and after etching.

Some very sharp pairs of straight vertical lines are visible in the web surface in Figure 9. They have an appearance similar to that of twin lamellae running down the surface of the web. Micrograph 11 shows these lines at higher magnification. Similar lines have been observed in other types of silicon ribbons.⁷ These twin related fault lines have probably developed due to over thinning of the web during seeding, resulting in twin plane outcropping during early stages of growth. The twin planes then can grow back into the web further down the crystal, but a mismatch in twin spacing and structure will generally develop.¹ A cross section of the web corresponding to Figure 16 is shown in Figure 17 where the twin plane mismatch is clearly visible.

In Figures 6, 8, and 9, complex arrays of slip bands are clearly visible on the web surfaces. Large numbers of dislocations have apparently been generated and propagated through the crystal. Some sources of these dislocations have been discussed,^{8,9} but others probably exist. Dislocation interactions in the interior of the web may result in generation of new dislocations. Figure 18 is a micrograph showing interaction between $[111]$ slip lines in the web region of the specimen in Figure 8. It is not yet clear what role this type of interaction might play in the degeneration of the web structure or in the development of high residual stresses in the crystal. Studies are now being directed at understanding these possible relationships. Dislocation-twin plane interaction may also affect crystal behaviour; this type of interaction is visible in Figure 16.

Some distinctly different surface lines are visible in the highly deformed web specimens in Figures 10 and 11. These lines have characteristics of twin boundaries. They appear to have a $[111]$ twin plane orientation as required by the diamond cubic lattice.

The lines in Figure 10 appear to have originated when a piece of oxide attached itself to the surface of a growing web. Some distinctly different twin traces are shown in Figure 11. These lines are commonly observed in highly deformed regions of polycrystalline web samples. Micrographs 19 and 20 show these lines at higher magnification. In Figure 20, there is further evidence of dislocation-twin plane interaction resulting in lineage.

Further studies will be directed at more positively identifying these defect lines and determining their origins and their effect on web properties. Once the origins are identified, it is likely that they can be eliminated by suitable process control.

Figure 6 Vertical fault lines in web region of crystal J-14 (Etched)

Figure 7 Fault lines in surface of crystal W26-2.8 (Etched)

Figure 8 Fault lines and slip bands in J52-1.3 (Etched)

Figure 9 Twin lines and slip bands in crystal W23-2.3 - (Etched)

Figure 10 Twin lines due to oxide on surface of web W48-1 (Unetched)

Figure 11 Twin lines in highly deformed polycrystalline region of web W23-2.9 (Etched).

Figure 12 Fault line on surface of web J14 (Etched) 200X

Figure 13 Apparent low angle grain boundary on surface of web W26-2.8 (Etched) 500X

Figure 14 Vertical fault line in J52-1.3 - (Unetched)
100X

Figure 15 Grain boundaries in Web J52-1.3 - (Etched)
100X

Figure 16 Apparent twin lamellae in web W23-2.3 (Etched)
200X

Figure 17 Cross section of W23-2.3 showing twin plane
mismatch 500X

Figure 18 Slip line interaction in J52-1.3 (Etched)
100X

Figure 19 Twin lines in polycrystalline region of W23-2.9
200X

Figure 20 Dislocation twin plane interaction in
W23-2.9 500X

3.0 PLANS FOR THE NEXT QUARTER

Experimental operation of the melt replenishment system and the vertical thermal gradient control system will continue in the RE and J web growth facilities. Thermal modeling and stress analysis will continue to evaluate addition geometry and operating conditions for the vertical thermal gradient control system. Thermal modeling will also continue for configurations suited to melt replenishment.

Other components of the stress tensor will be evaluated in addition to the Z component. The results will be compared with the residual stress measured in crystals grown under different conditions.

An argon flow system will be constructed to allow control of the gas flow in the region of the growth slot. This system is expected to serve as an additional tool for vertical thermal gradient control and to permit a wider choice of lid and top shield geometry without the accumulation of harmful oxide deposits.

The polysilicon pellet feeder will be improved to feed a single pellet with at least 98% reliability on each command. A hermetic enclosure will be built to enclose the necessary components and the feeder will be mounted on the melt replenishment system of the RE web growth facility.

Experimental web growth runs in the W facility will pursue reduced residual stress within the web while also seeking increasingly routine growth.

4.0 NEW TECHNOLOGY

No new technology was developed during this period.

5.0 REFERENCES

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6.0 APPENDIX

6.1 Summary of Characterization Data

Growth Run Detail Summary - Pages 39 through 53.

6.2 Updated Program Plan

6.2.1 Updated Milestone Chart

6.2.2 Program Labor Summary (updated Curve #696415A)

6.2.3 Program Cost Summary (updated Curve #696416A)

GROWTH RUN DETAIL SUMMARY

Run No.	Web No.	ΔT °C	Pull Rate cm/min.	Length cm	Width mm	Thickness μm	Comments
J-45	1	4.9	1.8	37	14.4/15.1	340	Repeat of J-44 Configurations 185.0 gms Si, 1×10^{17} DOPESIL
	2	4.1	2.7	56	7.1/10.4	-	
J-46	Not Productive						Short dogboned slot 66.6x6.3 min, two top shields, 186.2 gms Si, 1×10^{17} DOPESIL
J-47	1	3.9	1.7	32	8.7/11.1	380	Same Configuration as J-46 185.0 gms Si, 1×10^{17} DOPESIL
	2	3.9	1.7	52	11.7/16.5	305	
	3	4.1	1.7	39	7.6/11.2	160	
	4	4.2	1.7	73	10.1/17.1	210	
J-48	1	3.8	1.9	36	16.1/19.3	230	Same configuration as J-46 184.1 gms Si, 1×10^{17} DOPESIL. Crucible bottom ground.
J-49	1	4.5	1.6	108	17.4/28.8	240	Same configuration as J-46 184.1 gms Si, 1×10^{17} DOPESIL
	2	4.5	1.6	109	10.4/19.7	180	
	3	4.6	1.6	167	12.2/27.5	160	
	4	3.7	1.3	103	10.0/20.5	180	
J-50	1	3.2	1.8	129	13.3/22.1	150	Same configuration as J-46 185.7 gms Si, 1×10^{17} DOPESIL
	2	3.0	1.6	189	8.2/24.0	160	
J-51	1	4.1	2.9	37	7.4/9.4	240	80x6 mm dogboned slot, 3x3 mm level Single top shield, 2.6cm wide straight slot. 186.6 gms Si, 1×10^{17} DOPESIL
	2	4.4	2.7	43	10.6/12.5	272	
	3	4.6	2.1	107	4.2/11.7	320	
	4	4.3	2.0	20	13.2/14.8	318	
J-52	Not Productive						Repeat J-51 configuration with higher coil.
J-53	1	4.9	1.7	72	15.2/23.7	290	New lid: 8mm thick, slot 80x6mm, 12.7 mm dogbone holes, 6x6 mm bevel all around. Three top shields, lower two shaped to match bevel. 185.0 gms Si, 1×10^{17} DOPESIL
	2	4.5	2.0	91	17.8/27.0	160	
	3	3.7	2.0	60	14.7/19.9	125	
	4	3.7	1.9	168	11.2/24.6	125	

GR3WTH RUN DETAIL SUMMARY

<u>Run No.</u>	<u>Web No.</u>	<u>ΔT °C</u>	<u>Pull Rate cm/min.</u>	<u>Length cm</u>	<u>Width mm</u>	<u>Thickness μm</u>	<u>Comments</u>
J-54	1	4.3	2.0	82	17.0/23.9	200	Same configuration as J-53 185.3 gms Si, 1×10^{17} DOPESIL
	2	4.1	2.0	142	11.8/22.8	95	
J-55	1	4.3	2.0	50	10.3/15.2	-	Same configuration as J-53 185.5 gms Si, 1×10^{17} DOPESIL
	2	3.6	2.0	202	9.5/23.5	125	
	3	3.3	1.9	154	18.8/29.9	185	
J-56	1	3.8	1.9	44	8.0/12.6	340	Same configuration as J-53 except one of shaped top shields removed 184.9 gms Si, 1×10^{17} DOPESIL
	2	3.7	1.9	55	12.8/18.0	290	
J-57	1	4.1	1.9	120	14.2/27.9	180	Same configuration as J-53 185.7 gms Si, 1×10^{17} DOPESIL
	2	3.7	2.0	127	15.1/26.9	-	
	3	3.7	1.9	121	14.5/24.8	140	

GROWTH RUN DETAIL SUMMARY

Run No.	Web No.	ΔT °C	Pull Rate cm/min.	Length cm	Width mm	Thickness μm	Comments
J-58	1	3.8	1.9	25	15.8/17.9	290	Same configuration as RE-1 (80x6mm dogboned slot, two top shields) 185.3 gms Si, 1×10^{17} DOPESIL
	2	3.7	1.9	106	13.3/23.0	230	
	3	3.9	1.9	72	9.7/16.1	205	
	4	4.2	1.9	79	14.0/20.8	200	
	5	3.6	1.6	55	14.7/20.3	265	
	6	3.5	1.6	44	25.1/29.8	205	
J-59	Not Productive						To test effect on web quality of a wide view of bare hot lid, no top shields: Ice from ends of crucible. Thermal profile humped in center. 184.8 gms Si, 1×10^{17} DOPESIL.
J-60	Not Productive		Run aborted because of boiling coil cooling water.				Same as J-59 except side shields removed. 184.9 gms Si, 1×10^{17} DOPESIL
J-61	Not Productive						Same as J-59, except single top shield with 6.7x12.7 cm opening.
J-62	1	4.3	2.1	55	14.0/17.2	200	80x6.1 mm dogboned slot, two identical top shields with 4.7 mm set back 185.1 gms si, 1×10^{17} DOPESIL.
	2						
J-63	1	4.4	2.1	38	17.0/19.6	195	Same configuration as J-62 except upper top shield changed to wide oval to increase set back in slot region. 185.3 gms Si, 1×10^{17} DOPESIL.
	2	4.2	2.0	67	14.5/18.0	188	
J-64	1	3.5	19.9	167	14.5/25.9	155	New lid. Straight slot 80x4 mm, 5mmx45° bevel all around. Two top shields with 1 mm set backs 185.5 gms Si, 1×10^{17} DOPESIL.
	2	3.0	1.9	153	17.7/27.3	120	
	3	2.7	1.8	142	14.1/22.3	120	
	4	3.3	1.9	367	10.0/19.2	85	

GROWTH RUN DETAIL SUMMARY

Run No.	Web No.	ΔT °C	Pull Rate cm/min.	Length cm	Width mm	Thickness μm	Comments
J-65	1	3.6	1.9	58	16.2/20.1	210	Repeat J-64 configuration 184.5 gms Si, 1×10^{17} DOPESIL
	2	3.6	1.9	11°	10.3/13.9	165	
	3	3.1	1.8	145	17.3/27.0	155	
	4	2.7	1.7	101	17.1/23.1	138	
	5	3.3	17.	52	17.0/19.7	125	
J-66	1	3.1	1.9	107	12.4/18.3	185	Repeat J-64 configuration. Icing problems 184.8 gms Si, 1×10^{17} DOPESIL
		3.2	1.9	114	8.5/16.5	155	
J-67	1	3.3	1.9	46	15.0/18.1	185	Repeat J-64 configuration. Icing problems. 184.9 gms Si, 1×10^{17} DOPESIL
	2	3.3	1.9	63	12.3/17.2	165	
	3	2.5	1.7	50	9.7/12.9	-	
J-68	1	2.5	1.9	94	11.3/17.0	265	Same as J-64. Icing problems Temperature probe of susceptor gave no obvious reasons for icing. 184.9 gms Si, 1×10^{17} DOPESIL.
	2	3.2	2.1	84	11.2/15.2	150	
	3	3.8	2.0	31	16.2/17.8	165	
J-69	1	3.5	2.0	63	12.6/15.3	235	First test of dynamic afterheaters. 185.0 gms Si, 1×10^{17} DOPESIL.
	2	4.3	2.0	40	12.7/14.9	212	
J-70	1	3.8	2.0	53	11.5/16.3	250	Same configuration as J-69. After heaters letter aligned with slot. 184.8 gms Si, 1×10^{17} DOPESIL.
	2	3.6	2.1	24	14.6/15.8	200	
	3	3.0	2.1	44	13.7/13.0	160	
J-71	1	4.5	1.9	45	16.3/17.8	270	Same configuration as J-70. 185.0 gms Si, 1×10^{17} DOPESIL. Ice problems
	2	3.2	2.1	40	12.5/15.7	185	
	3	3.3	2.1	22	20.5/20.8	187	
	4	4.3	2.0	30	15.3/16.5	195	
J-72	Not Productive, due to excessive oxide formation and icing					80x4 mm straight slot, 5 mm x 45° bevel, 2 top shields afterheaters. 186.3 gms Si, 1×10^{17} DOPESIL.	

GROWTH RUN DETAIL SUMMARY

Run No.	Web No.	ΔT °C	Pull Rate cm/min.	Length cm	Width mm	Thickness μm	Comments
J-73	1	3.9	1.9	28	14.5/16.6	240	RE-1 configuration. No afterheaters Test crucible from new supplier. 185.3 gms Si, 1×10^{17} DOPESIL.
	2	4.3	2.0	31	19.4/17.2	260	
	3	4.5	2.0	34	11.7/14.1	220	
	4	3.9	1.9	35	14.5/17.1	234	
	5	4.9	1.7	48	20.4/20.6	223	
	6	4.0	1.7	48	22.2/26.8	-	
J-74	1	3.1	1.9	50	11.6/14.7	270	Same configuration as J-72, but no afterheaters 184.2 gms Si, 1×10^{17} DOPESIL
	2	3.2	2.0	61	12.6/14.5	220	
	3	4.9	2.0	12	32.1	-	
	4	3.0	1.9	67	17.3/20.4	185	
	5	3.2	1.6	94	11.8/14.0	230	
J-75	1	3.9	2.0	58	10.8/15.4	350	80x6 mm slot, 12.7 mm dogbones, 5 mm x 45° bevel all around. 2 full top shields 186.6 gms Si, 1×10^{17} DOPESIL
	2	3.6	2.0	91	13.0/18.3	289	
	3	3.3	2.1	71	15.6/19.0	195	
	4	3.7	2.1	101	12.8/16.6	140	
J-76	1	2.6	2.1	44	13.5/15.7	179	Same configuration as J-75, with afterheaters 178.8 gms Si, 1×10^{17} DOPESIL.
	2	2.9	2.1	111	13.0/18.0	158	
	3	3.1	2.0	43	12.5/14.4	155	

GROWTH RUN DETAIL SUMMARY

Run No.	Web No.	ΔT °C	Pull Rate cm/min.	Length cm	Width mm	Thickness μm	Comments
RE-16	1	5.8	1.8	32	8.6/11.9	352	Same configuration as RE-1 186.0 gms Si, 1×10^{17} DOPESIL
	2	5.7	1.7	33	11.0/12.8	285	
	3	5.7	1.5	38	13.2/16.7	310	
RE-17	1	4.3	1.7	47	12.1/16.1	230	Same configuration as RE-1 185.8 gms Si, 1×10^{17} DOPESIL
	2	4.2	1.7	36	6.3/9.7	290	
RE-18	1	5.6	1.7	186	8.8/26.4	-	Same configuration as RE-1 186.3 gms Si, 4×10^{17} DOPESIL (to produce lower resistivity material).
	2			58	11.0/15.8	180	
	3	5.4	1.5-1.4	166	11.9/29.5	263-210	
RE-19	1	4.1	1.7	27	10.0/11.9	650	New lid, 8.7 mm thick. Slot 80x6mm, 12.7mm dogbone holes. 5x5 mm bevel all around two top shields. 185.1 gms Si, 1×10^{17} DOPESIL Severe icing due to oxide falling into melt.
44 RE-20	1	2.9	2.2	61	9.2/12.9	240	Same configuration as RE-19 ;97/2 gms Si, 1×10^{17} DOPESIL
	2	2.7	1.9	126	8.5/16.7	310	
	3	3.2	1.8	120	9.9/18.5	262	
	4	3.3		116	6.7/13.8		
	a		1.8			204	
	b		2.6			96	
	c					60	
	5			125	9.7/18.1		
	a		1.8			188	
	b		2.4			110	
RE-21	1	4.5	1.8	66	9.5/13.3	370	Same configuration as RE-19 186.2 gms Si, 1×10^{17} DOPESIL
	2	4.1	1.7	46	10.1/14.1	350	
	3	3.3	1.7	41	13.8/16.0	290	
	4	3.2	1.8	124	10.5/19.2	200	
	5	3.6	1.7	31	16.9/19.2	210	
	6	3.6	1.5	46	15.6/20.0	230	
	7	3.6	1.5	156	12.0/26.3	195	

GROWTH RUN DETAIL SUMMARY

Run No.	Web No.	ΔT °C	Pull Rate cm/min.	Length cm	Width mm	Thickness μm	Comments
RE-22	1	4.7	1.5	29	9.8/12.5	310	Same configuration as RE-1 185.5 gms Si, 1×10^{17} DOPESIL Crucible bottom ground
	2	5.0	1.7	40	8.5/11.5	260	
	3	4.0	1.7	40	10.5/13.5	215	
	4	4.9	1.7 - 1.2	196	7.9/26.9	290	
RE-23	1	5.2	1.7	53	8.7/13.6	310	Same configuration as RE-1 183.9 gms Si, 1×10^{17} DOPESIL
	2	5.4	1.8	37	8.4/11.7	-	
	3	3.8	1.7	155	16.0/33.2	235	
	4	4.0	1.7	104	14.3/23.7	140	
	5	4.1	1.5	51	14.5/19.4	150	
	6	4.1	1.4	30	10.8/13.2	160	
	7	4.4	1.2	68	17.9/26.2	205	
RE-24	1	4.4	1.8	163	12.9/29.7	220	Same configuration as RE-1 186.5 gms Si, 1×10^{17} DOPESIL
	2	4.4	1.8	38	13.6/16.8	180	
	3	4.9	1.5	25	14.2/16.4	220	
	4	4.1		58	14.1/20.1	240	
45 RE-25	1	4.2	1.8	48	13.8/18.6	290	Same configuration as RE-1 185.2 gms Si, 1×10^{17} DOPESIL
	2	4.6	1.8	124	17.1/35.0	200	
	3	4.9	1.8	122	17.6/30.1	155	
	4	4.6	1.5	117	9.4/21.7	168	
	5	4.8		95	10.5/20.3	180	
	6	4.1	1.4	40	16.4/20.9	160	
RE-26	1	3.9	1.8	97	13.9/23.4	270	Same configuration as RE-1 185.1 gms Si, 1×10^{17} DOPESIL
	2	4.1	1.8	64	16.0/21.6	220	
	3	4.4	1.8	159	15.1/30.0	170	
	4	4.3	1.5	56	7.8/14.0	280	
	5	4.1	1.5	44	13.9/18.8	235	
RE-27	1	5.2	1.8	92	13.0/21.2	250	Same configuration as RE-1 185.1 gms Si, 1×10^{17} DOPESIL
	2	5.1	1.8	91	6.0/13.5	160	
	3	4.8	1.7	137	12.5/26.3	168	
	4	5.7	1.4	37	19.0/23.5	220	

GROWTH RUN DETAIL SUMMARY

Run No.	Web No.	ΔT °C	Pull Rate cm/min.	Length cm	Width mm	Thickness μm	Comments
RE-28	1	5.9	1.9	90	9.2/18.4	253	Same configuration as RE-1 185.9 gms Si, 1×10^{17} DOPESIL
	2	5.6	1.7	84	16.2/26.1	230	
	3	5.0	1.7	24	18.8/21.5	250	
	4	5.0	1.8	46	21.0/26.0	190	
	5	5.0	-	184	16.3/36.0	-	
	a		1.7			185	
	b		1.5			210	
	c		1.4			240	
	d		1.1			330	
	6	5.0	1.5	77	17.1/24.6	150	
RE-29	1	5.1	1.9	31	13.7/16.1	225	Same configuration as RE-1 186.0 gms Si, 1×10^{17} DOPESIL
	2	3.5	1.9	48	10.3/13.2	170	
	3	3.5	1.6	193	11.4/25.8	180	
	4	4.3	1.6	93	11.1/19.6	155	
RE-30	1	4.0	1.9	149	14.9/28.1	200	Same configuration as RE-1 185.2 gms Si, 1×10^{17} DOPESIL
	2	4.0	1.5	115	15.2/26.8	180	
RE-31	1	5.4	1.8	37	13.5/18.4	310	Same configuration as RE-1 185.9 gms Si, 1×10^{17} DOPESIL
	2	4.0	1.9	95	9.8/17.1	210	

GROWTH RUN DETAIL SUMMARY

Run No.	Web No.	ΔT °C	Pull Rate cm/min.	Length cm	Width mm	Thickness μm	Comments
RE-32	1	3.3	1.9	68	13.0/19.2	170	Same configuration as J-53 (80x6mm, dog-bone, 3 top shields, two lower bent to match top 3 mm of bevel) oxide collects on lower top shields 185.0 gms Si, 1×10^{17} DOPESIL.
	2	4.2	1.5	52	14.7/20.5	230	
	3	4.2	1.8	61	14.1/18.9	122	
	4	4.2	1.4	68	18.3/25.2	125	
	5	4.2	1.4	77	17.7/24.8	100	
RE-33	1	4.9	1.8	107	12.0/22.0	265	RE-32 lid, single bent top shield, 2 standard. 185.5 gms Si, 1×10^{17} DOPESIL.
	2	4.3	1.9	72	16.2/21.7	180	
	3	4.1	1.9	149	15.6/27.9	170	
	4	3.9	1.8	134	16.8/25.5	120	
	5	4.0	1.7	67	17.5/23.6	140	
RE-34	1	2.9	2.1	68	10.0/16.1	232	Same configuration as RE-33. 187.5 gms Si, 1×10^{17} DOPESIL.
	2	3.7	2.1	37	14.0/15.6	250	
	3	3.1	2.1	19	16.7/17.8	-	
	4	3.2	2.1	120	11.5/21.9	165	
	5	2.7	1.5	71	9.5/14.4	165	
	6	3.5	1.9	133	13.8/23.2	153	
RE-35	Not Productive						RE-32 lid, 3 flat top shields. Excessive oxide and icing problems. Center to crucible wall profile too flat.
RE-36	Not Productive						RE-32 lid. 2 full top shields, plus 1 over ends only. Tendency for web to start poly.
RE-37	Not Productive						Same configuration as RE-36, except lower 2.5 cm of side shields removed. Web tended to start poly.
RE-38	Not Productive, First trial of manual feed system. See text.						Lid with 66x6.3 mm dogboned slot, two top shields crucible with barrier.
RE-39	Not Productive. Provision made to flow Ar through feed tube at known rates. Determination of flow rates required to keep feed tube clear of oxide.						

GROWTH RUN DETAIL SUMMARY

Run No.	Web No.	ΔT °C	Pull Rate cm/min.	Length cm	Width mm	Thickness μm	Comments
RE-40	1	2.3	2.0	131	8.4/17.8	212	Same configuration as RE-1 184.2 gms Si, 1×10^{17} DOPESIL
	2	3.2	2.1	85	10.6/15.9	165	
	3	3.2	1.8	74	-	-	
RE-41	1	4.1	1.9	82	15.0/22.8	232	Same configuration as RE-1 185.9 gms Si, 1×10^{17} DOPESIL.
	2	3.7	2.1	133	10.8/20.8	165	
	3	3.6	1.8	135	11.9/24.6	173	
RE-42	1	2.9	1.9	85	12.1/16.6	240	80x4 mm straight slot beveled 5 mm x 45°, 2 top shields. 185.4 gms Si, 1×10^{17} DOPESIL. Ice repeatedly nucleated by oxide falling into melt from under lid.
RE-43	1	3.0	2.2	46	15.3/19.8	177	RE-38 configuration, with feed. 183.6 gm Si, 1×10^{17} DOPESIL.
	2	2.4	1.9	100	14.4/22.4	171	
48 RE-44	1	3.6	1.8	-	-	562	Same configuration as RE-43, with feed. 180.1 gms Si, 1×10^{17} DOPESIL Problems with floating ice.
	2	4.0	1.8	47	9.6/14.7	420	
	3	3.5	1.9	44	12.9/16.4	246	
	4	3.1	2.1	94	10.5/17.8	185	
	5	-	2.0	-	-	-	
RE-45	1	3.4	2.4	67	12.3/16.8	183	Same configuration as RE-43, with feed 183.1 gms Si, 1×10^{17} DOPESIL. Feed tube clogged before feed could be initiated icing.
RE-46	1	2.3	2.2	73	10.5/15.8	140	80x6 mm slot, 12.7 dogbones. 5 mm x 45° bevel all around, 3 top shields, lower shaped to bevel. 184.9 gms Si, 1×10^{17} DOPESIL Excessive oxide build up.
	2	3.8	2.1	96	11.5/17.2	125	
RE-47	1	4.1	1.8	90	13.1/23.3	250	RE-43 lid, 2 full top shields, feed system. 185.4 gms Si, 1×10^{17} DOPESIL Excessive oxide on lower top shield.

GROWTH RUN DETAIL SUMMARY

<u>Run No.</u>	<u>Web No.</u>	<u>ΔT</u> <u>°C</u>	<u>Pull Rate</u> <u>cm/min.</u>	<u>Length</u> <u>cm</u>	<u>Width</u> <u>mm</u>	<u>Thickness</u> <u>μm</u>	<u>Comments</u>
RE-48	Aborted during melt down, Si touched lid, immediate reaction between moly + Si						
RE-49	1	3.5	1.9	87	11.4/15.9	110	New susceptor. New lid design. 50x4 mm straight slot, 5 mm x 45° bevel all around 2 full top shields, 1 mm setbacks 176.7 gms Si, 1×10^{17} DOPESIL
	2	2.8	1.8	77	14.6/16.5	120	
	3	2.3	1.5	209	10.5/21.9	120	
	4	2.9	1.1	204	14.1/25.0	170	

GROWTH RUN DETAIL SUMMARY

<u>Run No.</u>	<u>Web No.</u>	<u>ΔT °C</u>	<u>Pull Rate cm/min.</u>	<u>Length cm</u>	<u>Width mm</u>	<u>Thickness μm</u>	<u>Comments</u>
W-21	4	4.2	1.45	88.9	9.6/16.4	270	195.5 gm Si; 1×10^{17} DOPESIL Lid 3U, Shield 4
W-22	5	3.6	1.45	211	7.7/26.0	272	Purpose: study effect of melt level on stresses 120.2 gm Si; 1×10^{17} DOPESIL LID 3 U, Shield 4
W-23	1	4.5	1.90	120	7.9/16.2	269	Purpose: evaluate melt level 121.4 gm Si, 1×10^{17} DOPESIL Lid 3U, Shield 4
	2	3.6	1.54	115	11.2/18.6	270	
W-24	1	5.1	1.90	69	13.1/18.1	312	Lid 3U, Shield 4 Low argon flow rate 120.3 gm Si; 1×10^{17} DOPESIL
W-25	Non-Productive						Repeat W-23
W-26	1	3.9	1.9	137	12.0/20.2	241	Repeat W-23 120.3 gm Si; 1×10^{17} DOPESIL
	2	4.5	1.6	215	13.9/31.2		
W-27	5	5.7	1.45	207	11.7/30.7	240	Repeat W-23 121.0 gm Si; 1×10^{17} BORON
W-28	Non-Productive						New Lid 8U Shield 4
W-29	Non-Productive						Repeat W-23
W-30	1	5	1.62	104	14.6/22.4	240	Lid 3U, Shield 4 120 gm Si; 1×10^{17} DOPESIL
W-31	Non-Productive						Lid 3U, Shield 1 120 gm Si; 1×10^{17} DOPESIL Lower Coil
W-32	Non-Productive						Lid 3U, Shield 1 120.8 gm Si; 1×10^{17} DOPESIL
W-33	Non-Productive						Lid 8U, Shield 1 Lower coil position 119.8 gm Si; 1×10^{17} DOPESIL

GROWTH RUN DETAIL SUMMARY

<u>Run No.</u>	<u>Web No.</u>	<u>ΔT °C</u>	<u>Pull Rate cm/min.</u>	<u>Length cm</u>	<u>Width mm</u>	<u>Thickness μm</u>	<u>Comments</u>
W-34	2	5.0	2.0	145	0.3/15.1	183	Repeat W-33 119.6 gm Si; 1×10^{17} DOPESIL
	3	6.2	2.1	84	12.5/16.3	160	
W-35	Non-Productive						Lid 8U, Shield 1 Lower Coil
W-36	Non-Productive						Lid 8U, Shield 1 space between lid and susceptor; raised coil 121.8 gm Si; 1×10^{17} DOPESIL
W-37	2	3.5	1.9	181	9.1/20.2		Repeat W-36 122.8 gm Si; 1×10^{17} DOPESIL
W-38	Non-Productive						Repeat Lids of W-36 Closed holes in Susceptor 119 gm Si; 1×10^{17} DOPESIL
W-39	Non-Productive						Lid 8U Shield 2 Shield 1 119.2 gm Si; 1×10^{17} DOPESIL

GROWTH RUN DETAIL SUMMARY

<u>Run No.</u>	<u>Web No.</u>	<u>ΔT °C</u>	<u>Pull Rate cm/min.</u>	<u>Length cm</u>	<u>Width mm</u>	<u>Thickness μm</u>	<u>Comments</u>
W-40	1	4	1.45	106	10.0/16.4	252	Evaluate Lid 8u with shields - S (1 + 2) 119.2 gm Si; 1×10^{17} DOPESIL.
W-41	1	2.6	1.45	368	10.3/21.4	165	Evaluate Lid. 8u and shields S (1 + 2) at lower coil height. 119.8 gm Si; 1×10^{17} DOPESIL.
W-42	1	4.1	1.62	123	9.6/21.5	307	Repeat Run W-41
	4	3.1	1.45	121	11.5/20.6	205	
W-43	1	5.0	1.62	145	9.4/19.8	245	Repeat Run W-41 123 gm Si; 1×10^{17} DOPESIL
	2		1.69	137	8.4/18.2	170	
W-44	3	3.8	1.62	420	10.7/20.3	63	Repeat Run W-41 119.1 gm Si; 1×10^{17} DOPESIL
W-45	1		1.35	520	8.3/21.8	170	Evaluate short, unbeveled slot lid 14S, shield S (1 + 3) 121.8 gm Si; 1×10^{17} DOPESIL
W-46	Non-Productive;						Repeat Run W45 120.6 gm Si; 1×10^{17} DOPESIL
W-47	1	4.3	1.35	500	11.9/20.0	175	Repeat Run W45. Web Split when unreeled 118.9 gm Si; 1×10^{17} DOPESIL.
W-48	1			62	13.7/15.8	180	Repeat W-45 120.6 gm Si; 1×10^{17} DOPESIL.
W-49	1	1.6	1.35	237	11.0/16.4	161	Repeat W-45 120.7 gm Si; 1×10^{17} DOPESIL.
W-50	1	4.0	1.54	194	11.3/14.9	200	Evaluate Lid 14T with shields S (1 + 3) 121.8 gm Si; 1×10^{17} DOPESIL
W-51	1	3.5	1.35	237	14.3/22.1	210	Repeat W-50 122.6 gm Si; 1×10^{17} DOPESIL.
W-52	1	3.2	1.40	385	12.5/22.0	190	Repeat W-50 119.7 gm Si; 1×10^{17} DOPESIL.

GROWTH RUN DETAIL SUMMARY

Run No.	Web No.	ΔT °C	Pull Rate cm/min.	Length cm	Width mm	Thickness μm	Comments
W-53	Non Productive: Oxide Problem on Lid						Evaluate lid 3U with S (1 and 3)
W-54	Non Productive: Oxide Problem on Lid						Repeat W-53
W-55	1	1.7	1.45	305	13.2/22.6	160	Repeat W-50 126.7 gm Si; 1×10^{17} DOPESIL
W-56	1	2.1	1.62	450	12.1/22.5	220	Repeat W-50 124.2 gm Si; 1×10^{17} DOPESIL
W-57	1	2.7	1.45	230	11.1/18.0		Repeat W-50 127.1 gm Si; 1×10^{17} DOPESIL.
W-58	1	3.8	1.62	217	12.9/22.0	190	Repeat W-50 127.1 gm Si; 1×10^{17} DOPESIL.
W-59	1	1.7	1.75	187	11.0/14.0		Repeat W-50 127.1 gm Si; 1×10^{17} DOPESIL
W-60	1	3.7	1.69	210	12.0/21.9		Repeat W-50 131.1 gm Si; 1×10^{17} DOPESIL
W-61	1	2.0	1.75	340	10.3/18.6	150	Repeat W-50 127.1 gm Si; 1×10^{17} DOPESIL
W-62	Non-Productive						Lid 14+ Shields 1 and 3
W-63	Non-Productive						Lid 14+ Shields 1 and 3
W-64	1	5	1.8	583	12.4/21.9	131	Lid 14+ Shields 1 and 3 125.1 gm Si; 1×10^{17} DOPESIL
W-65	Non-Productive						
W-66	1	5	1.6	185	9.6/19	180	Lid 14U Shields 1 and 3 121.5 gm Si; 1×10^{17} DOPESIL
	2	5	1.6	86	18.3/21.4	250	
W-67	1	5	1.7	640	8.8/22.0	150	Lid 14U Shields 1 and 3 118.1 gm Si; 1×10^{17} DOPESIL

MILESTONE CHART

JPL CONTRACT 954654 - PHASE II

TASKS/MILESTONES

1978

1979

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1. EXISTING WEB GROWTH FACILITIES
 - a. Operate Facilities
 - b. Demonstrate $12 \text{ cm}^2/\text{minute}$
 - c. Demonstrate $25 \text{ cm}^2/\text{minute}$
2. MODIFY EXISTING WEB GROWTH MACHINE
3. OPERATE MODIFIED MACHINE
4. DYNAMIC THERMAL TRIMMING
 - a. Develop dynamic thermal trimming capability
 - b. Evaluate and modify thermal trimming
5. MELT REPLENISHMENT
 - a. Develop and demonstrate melt replenishment
 - b. Utilize melt replenishment capability
6. PERFORM SEEDING VARIATIONS AND STRUCTURAL CHARACTERIZATION
7. DEVELOP AND OPTIMIZE LID GEOMETRY AND UTILIZE THERMAL TRIMMING
8. PERFORM THERMAL MODELING
9. PROVIDE SOLAR CELLS AND WEB SAMPLES AS REQUIRED
10. UP-DATE ECONOMIC ANALYSIS
11. SUPPORT MEETINGS AS REQUIRED
12. PROVIDE REQUIRED DOCUMENTATION

Program Labor Summary JPL 954654, Phase II

Program Cost Summary JPL 954654 Phase II