PHASE 2 OF THE ARRAY AUTOMATED ASSEMBLY TASK
FOR THE LOW COST SILICON SOLAR ARRAY PROJECT

Third Quarterly Report, April 1—June 30, 1978

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July 31, 1978

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MASTER

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Solar Energy

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1. SUMMARY

During the third quarter of this program, development effort has been applied to front junction and back surface field region formation and to high speed application of AR coatings to ribbon material. Effects on cell performance of various surface preparation procedures for web silicon material have also been studied. Ultrasonic seam bonding of foil interconnects to cell metallization has been identified as a potentially higher throughput, lower cost method of interconnection than producing discrete bonds.

Collecting junctions have been made in wafer cells using reagent grade POCl_3 , containing titanium at the 20 ppma level, and in such material doped with Ti to the 100 and 500 ppma levels using TiCl_4 . No electrical effect of Ti doping was detected. This extended the finding of work in the first quarter that titanium concentrations at the 20 ppma level in reagent grade POCl_3 do not degrade cell performance in comparison to those produced using electronic grade (< 0.02 ppm Ti) POCl_3 . Although this impurity can play a strong role in lifetime degradation if introduced at low concentrations into a silicon melt, as a contaminant in POCl_3 it appears to be benign under the junction preparation conditions which were used.

Cells with boron diffusions made from boron-doped glasses deposited in a Silox^(R) reactor have shown back surface field action comparable to that in cells using glasses formed in a cold wall horizontal reactor. The former method is more conservative of material and more compatible with high throughput processing of ribbon silicon material.

Antireflection coatings of TiO_2 in the 600 Å range of thickness have been prepared by pulling from liquid precursor solutions at speeds ranging to 40 ft/min. Speeds above 10 ft/min are considered necessary for high throughput processing of continuous ribbon silicon. At 25 ft/min,

the contribution to selling price of this process is estimated to be about \$0.009/peak watt, with the cost of unrecovered alcohol being the major price component.

Several methods of preparation of the web silicon surface have been considered with regard to ultimate cell performance. Conventional cleaning methods used for integrated circuit processing of Czochralski wafers have not been adequate for most of the material used to date on the program. Etching about 10 μm of such silicon web in CP-4 solution gives the highest performance. Cleaning with sulfuric acid solution is somewhat less effective, but suggests that surface species related to molybdenum may be implicated in suppression of cell performance. Recent work with somewhat higher resistivity web silicon raises the possibility that etching may not be required. With this material, cells having back surface field regions on etched or unetched substrates gave comparably high performance.

2. INTRODUCTION

The key objective of this program is to establish a process sequence and to develop key process steps for low cost manufacturing of solar arrays from dendritic web, single crystal, silicon in ribbon form. Specifically, all costs, including web silicon at \$0.17/watt, are to be considered with the aim of producing encapsulated modules of 10% conversion efficiency for a selling price of \$0.50/peak watt in 1975 dollars.

A simplified process sequence, serving as the initial basis for development work on this program, was presented earlier.* Since dendritic web silicon can be handled as long lengths of ribbon through most of the cell fabrication steps (cleaning, junction formation, AR coating and metallization) conceptual processes for continuous processing have been proposed. In most cases, the operation of a proposed process as a continuous, rather than a batch, method should lead to lower costs in materials, equipment and labor.

In the automated, simplified, process sequence proposed for fabrication of web solar cells, there is no extensive cleaning procedure prior to junction formation. However, since the dendritic ribbon growth process is not yet fully developed, it has been necessary to perform certain cleaning and etching steps to achieve maximum cell efficiency. These are discussed in Section 3.1

The cost advantage of using reagent grade POCl_3 in the active junction fabrication of n+p silicon solar cells has been discussed in detail in the first quarterly report. From the cell characteristics data presented therein, it has also been demonstrated that cells fabricated

* Ref. 1, Sec. 3.1.

with lower purity POCl_3 (Baker Reagent) were equivalent to those made with electronic grade POCl_3 . Titanium (at 20 ppm) in the reagent POCl_3 was the most sensitive cell degrading impurity involved in that comparison. New experiments, conducted with deliberate introduction of extra TiCl_4 in POCl_3 diffusion sources, are discussed in Section 3.2. In Section 3.2, experiments with POCl_3 sources deliberately doped with Ti are discussed, along with results on base line cells with BSF regions prepared with doped glass films deposited using a Silox^(R) reactor systems.

Earlier, results have been reported for AR coating layers prepared by pulling dendritic web silicon ribbons from solutions containing organometallic precursors of TiO_2 .^{*} For those cases, relatively slow pull rates (~ 1 ft/min) were used. A higher pull rate will probably be required in future applications of this process. Section 3.3 gives results of experiments for pull speeds ranging to 40 ft/min.

Metallization and interconnection topics are discussed in Sections 3.4 and 3.5. Finally, in Sections 3.6 and 3.7, comprehensive effects of cell processing for web material and results on selection of web material suitable for cell fabrication for module assembly are treated.

* Ref. 1, pages 11-14.

3. TECHNICAL RESULTS

3.1 Substrate Preparation: Cleaning Studies

The program plan for the ARRAY project does not provide for extensive cleaning of the silicon web before diffusion. However, this plan anticipates that the web will be diffused immediately after growth (before significant surface oxidation occurs) and that the web growth process will be developed to the point that surface contaminants will not be a problem. Neither of these conditions is presently met. Therefore, throughout this program studies have been carried out to determine the simplest and most effective cleaning procedure prior to diffusion. It is still expected that when the above two conditions are met, the cleaning process will not be required.

The cleaning processes tested were:

1. HF Swab	Removal of lightly adhering oxides
2. 10:1 :: H ₂ O:HF DIP	Removal of surface oxides
$\text{NH}_4\text{OH} + \text{H}_2\text{O}_2 + \text{H}_2\text{O}$	Removal of surface metallic impurities
$\text{HCl} + \text{H}_2\text{O}_2 + \text{H}_2\text{O}$	
3. Hot H ₂ SO ₄ (160°C)	Cleaning etch specific for Mo oxides and silicides
4. Chemical Polishing	Si etching in a CP-4 solution
Material removal rate $\approx$ 1-3 $\mu\text{m}/\text{min}$

Treatment #2 is referred to as normal cleaning, generally used in the fabrication of semiconductor devices.

Table 1 summarizes the results obtained. The data are for a large number of runs on web samples from various ribbon runs. These results have been obtained a number of times and the trend shown is quite reliable.

Table 1

Normal Ranges for Conversion Efficiency and Open Circuit Decay Lifetime
of Dendritic Web Solar Cells
as a Function of Pre-Diffusion Cleaning (No AR coating)*

	<u>Treatment</u>	<u>Efficiency (%)</u>	<u>τ_{OCD} (μ sec)</u>
No Back Surface Field	HF Swab	6.5 - 7.0	< 1 - 1.5
	Normal Cleaning	7.0 - 7.5	1 - 2
	H ₂ SO ₄	7.5 - 8.2	1 - 2
	Chemical Polishing	8.0 - 8.5	1.5 - 2
Back Surface Field	HF Swab	--	--
	Normal Cleaning	7.5 - 8.5	1.5 - 10
	H ₂ SO ₄	8.0 - 10.0	2 - 40
	Chemical Polishing	8.5 - 10.3	2 - 40

* Web was p-type of 5 ohm cm nominal resistivity.

In general, the data show that some type of cleaning is required if the web cells are to approach their ultimate efficiency. Several comments should be made about the specific cleaning steps.

The observation that normal cleaning is relatively ineffective is an indication that the contaminant is not the usual metallic or organic material found on silicon that degrades other semiconductor devices. The H₂SO₄ cleaning was initiated when it was suspected that Mo compound might be involved as surface contaminant (JPL Contract 954331). In associated work using deep level spectroscopy, a trap level was found which was tentatively identified as Mo. The occurrence of Mo contamination is not unlikely since the metal is used for the susceptor and heat shields in the growth furnace. The H₂SO₄ cleaning is quite effective in increasing cell efficiency. Somewhat higher efficiency is realized if the sample is chemically polished. In this etching a total of 10-15 μ m is removed. Since the highest values of efficiency are associated with this treatment,

it is probable that some of the contaminant extend into the bulk of the material.

It will be shown in Section 3.6 that with a series of web crystals produced recently with a higher resistivity, the effect of chemical polishing is not straightforward. In several instances cells prepared from chemical polished (CP) material were actually poorer than cells prepared from material which had been cleaned with H_2SO_4 . This effect will be discussed in that section.

3.2 Junction Formation

3.2.1 Front Junction Preparation Using Ti-Doped $POCl_3$

Reagent grade $POCl_3$ (20 ppma Ti concentration) was contaminated with Ti to 100 and 500 ppma levels by liquid phase dilution with 99.9999% $TiCl_4$. Cells of the n+p type were fabricated using the three $POCl_3$ diffusion sources. Float-zone silicon wafers (2 to 4 ohm-cm, p-type, (111)-orientation) were used as substrates. Table 2 shows a summary comparison of these characteristics data for those cells. The 4% higher efficiency for cells from the 500 ppma Ti source is not significant.

The lack of effect on cell performance of high concentrations of Ti in the $POCl_3$ source as compared with deliberate Ti doping of the growing crystal may reflect the fact that stable oxide glasses are formed during the n+ diffusion, making this particular cell degrading impurity unavailable for diffusion into silicon. To verify this contention, the oxide glasses formed during these diffusions (all less than 500 Å thickness) were analyzed by secondary ion mass spectroscopy (SIMS). The relative ratios of integrated intensities for the mass numbers 47 (PO) and 48 (Ti) were computed for each type of glass and found to give relative Ti concentration ratios of 1:1.56:2.65. This is much smaller than the starting ratios of 1:5:25. Taken with the results of Table 2, this supports the idea that the increased Ti concentrations in the formed glasses are not available for performance degradation of the cells.

TABLE 2

Comparative Characteristics of Uncoated n+p Cells Fabricated
with POCl_3 Sources of Several Ti Concentrations

Ti Concentration in POCl_3 Source	τ_{OCD} (μs)	J_{SC} (mA/cm^2)	V_{OC} (mv)	Fill Factor	Efficiency %	No. of 1 cm^2 Cells
~ 20 ppma	5.21	22.18	544	0.698	8.9	48
~ 100 ppma	5.06	22.36	530	0.711	8.9	48
~ 500 ppma	5.02	22.56	540	0.721	9.3	42

Most of the difference between the experimental Ti ratios of 1:1.56:2.65 and the source Ti ratios of 1:5:25 can be accounted by the relative difference of vapor pressures of the two components (p_{POCl_3} @ $20^\circ\text{C} \approx 35$ mm Hg and p_{TiCl_4} @ $20^\circ\text{C} \approx 10$ mm of Hg). Furthermore, the mechanisms of oxidation of these two components would also make the solid glass poorer in Ti content. POCl_3 oxidizes in the gas phase to $\text{P}_2\text{O}_5(\text{g})$. The homogeneously produced gaseous P_2O_5 is available to react with the silicon and form the glass diffusion source. On the other hand, TiCl_4 oxidizes to $\text{TiO}_2(\text{s})$. The homogeneously formed solid TiO_2 particles should be exhausted. Those produced on the silicon surface are not incorporated into the glass, and are also probably exhausted.

3.2.2 Boron Doped-Oxide Source BSF Cells

Using 2-4 $\Omega\text{-cm}$ 2" dia. Monsanto(111) p-material (baseline) $n^+ pp^+$ cells were fabricated to (1) exercise our new AMS-1000 "Silox" doped-oxide reactor for boron-doped BSF formation and (2) check on the requirement of front surface undoped oxide masking during formation of the BSF region.

The AMS-1000 Silox^(R) reactor is an efficient, low-cost vapor phase oxidation system for depositing doped and undoped SiO_2 films at 350° to 450°C . It has a typical hourly throughput of 120 2-inch wafers with an overall film thickness uniformity of $\pm 5\%$. The AMS-1000 reactor system consists of a resistance heated wafer carrier and gas dispersion head about 100 mils above the carrier. Deposition is accomplished by placing wafers on the carrier mechanism which passes below the dispersion head at a pre-programmed rate of travel. The dispersion head injects an approximately laminar flow of oxygen, silane and/or the dopant hydride (PH_3 or B_2H_6) in a nitrogen carrier into the reaction zone where the reactants combine to deposit SiO_2 . Between deposition cycles the dispersion head is automatically purged to ensure compositional purity, and it is water cooled to minimize gas phase reaction.

These n^+pp^+ cells were processed by the standard boron doped oxide technique with the BSF source film being deposited under the following conditions:

- (1) Nominal deposition temperature = $420^\circ \pm 4^\circ\text{C}$.
- (2) 15% SiH_4 flow = 160 cc/m, 5% B_2H_6 flow = 370 cc/m, total N_2 flow = 5.7 l/m, and O_2 flow = 250 cc/m.
- (3) Doped-film thickness $\sim 4600 \text{ \AA}$ (two passes), and undoped capping film thickness $\sim 2000 \text{ \AA}$ (two passes) with the front surface masking undoped SiO_2 thickness $\sim 1000 \text{ \AA}$.

The BSF film was annealed for 4 hrs at 1000°C in 2.5 l/m each of N_2 and O_2 with 2"/5 min. pull-rate to generate a boron-diffused layer with $X_j \sim 1.9\mu$ and $R_s = 35 \pm 0.5 \Omega/\square$. The active n^+p junction was formed by 825°C , 200m POCl_3 diffusion with a $R_s = 35 \pm 0.5 \Omega/\square$. Evaporated Ti-Pd-Ag front and Al back metallizations were used with no AR coating.

Cell characteristics data is shown in Table 3. Results for cells prepared using a similar process, but with a horizontal cold-wall reactor were given in Section 3.1.2 of Ref. 2. The most recent results are comparable or slightly better than the earlier ones, indicating that the Silox^(R) reactor approach has no performance disadvantages in its application.

3.3 Antireflection Coatings by Dip Processing

Excellent antireflection coating results have been obtained by the use of specially prepared TiO_2 layers on silicon wafers. In this technique an organic precursor of TiO_2 in an alcohol solvent is applied to the silicon and subsequently baked to produce an essentially pure, compact TiO_2 film. The refractive index of the layers, approximately 2, is ideal for the purpose. Excellent uniformity ($\sim 2 \text{ \AA}$) over the 30 cm length of the baked layers was achieved by the dip process at speeds of 30 cm/min ($\sim 1 \text{ ft/min}$). A preliminary economic analysis for this method of AR coating silicon-ribbon has been made.*

*Ref. 2, Section 3.2

Table 3
 CHARACTERISTICS OF n^+pp^+ BASE-LINE CELLS FABRICATED WITH AMS-1000 REACTOR
 PRODUCED BACK SURFACE FIELD

Cell Groups	τ_{OCD} (μs)	$J_{\text{sc}2}$ (ma/cm^2)	V_{OC} (mv)	Fill Factor	Efficiency %	No. of 1 cm^2 cells
2-4 Ω -cm p (111) CZ Wafer (9 mils) without SiO_2 front mask	10.45	22.46	569	0.772	10.43	36
2-4 Ω -cm p (111) CZ Wafer (9 mils) with SiO_2 front mask	12.83	23.12	564	0.768	10.60	35

At a speed of 25 ft/min, the selling price contribution of the AR coating step using the model of Ref. 2 Section 3.2 is estimated to be about \$0.009/watt. This figure is for a four step coating process producing $1.5 \times 10^5 \text{ m}^2$ of coated silicon ribbon in a year, capable of 15 MW peak power generation.

Presently AR coatings are applied on silicon ribbons from a metal-organic based solution at the rate of approximately 1 ft/min. Experiments were carried out on the feasibility of increasing this rate an order of magnitude or more to allow operation in a range for optimum speeds as discussed in Ref. 2. Increased pull rates require alteration of the viscosity of the precursor solution.

Stainless steel ribbons (100 cm long and 1.3 cm wide) were immersed in AR coating solution with concentrations of 0.5, 1.0, 2.0 and 3.7 weight percent equivalent oxide. The ribbons were then withdrawn from the solution at various speeds up to 35 ft/min. After baking the coating at 400°C, the thicknesses were measured and related to the rate of withdrawal.

Figure 1 shows the quarter wave optical thickness of the coating as a function of the square root of the withdrawal rate for various solutions. The figure also shows the lines of ideal behavior predicted by theory.

There is reasonably good agreement between the theory and experimental results with the exception of the 0.5% concentration solution. For this low concentration, the thickness of the deposited film appears to become relatively independent of the withdrawal rate at high speeds. The thickness, however, was slightly below the desired thickness for quarter wave films. The thickness of the coating derived from the 1% solution also appears to level off above the 15 ft/min rate and is slightly higher than the desired thickness.

As a result of this experiment, it has been determined that 3.7% solution at 0.6 ft/min, 2.0% solution at 2.7 ft/min, and 1.0% solution at 9.0 ft/min withdrawal rate will deposit a quarter wave thick optical film.

DIP COATING OF STAINLESS STEEL STRIP

$$(\lambda_{\min} = 4 \times \text{ref. ind.} \times \text{thickness})$$

Fig. 1 Predicted and experimental results for TiO_2 coating thickness (as related to the wavelength giving minimum reflectance) as a function of withdrawal speed from TiO_2 precursor solutions of various concentration by weight.

For the 0.5 concentration solution, however, the thickness of the film was independent of the withdrawal rate at high speeds (> 15 ft/min). The wavelength for the reflectance minimum remained more or less constant at $5000 \text{ \AA}$ (film thickness, slightly over $600 \text{ \AA}$). This phenomenon has considerable significance, indicating that the coating might be applied at extremely high rates, e.g., 40 ft/min or higher in continuous automated mass production, thus lowering cost.

3.4 Metallization

The metallization scheme chosen for initial process development calls for Ti-Pd-Ag on the sun side of the cells; vacuum evaporated aluminum on the dark side.

Prior to the metallization process step, the silicon web has been antireflection coated and this coating has been fired to produce a TiO_2 film. With a positive photoresist, the antireflection coating is etched from the contact areas; the unexposed photoresist is allowed to remain on the cells through part of the metallization process. Titanium and palladium ($200 \text{ \AA}$ of each) are separately vacuum evaporated onto the sun side of the cell. Removal of the remaining photoresist then rejects the thin metal film from all areas except the contact regions.

The metal contact areas are electroplated with silver to a thickness of $4\text{--}7 \text{ \mu m}$ in order to furnish the required current carrying capability. Thickness of the deposited silver layer is easily controlled through the regulation of current density (normally 10 mA/cm^2) and plating time (normally 12 minutes for $4 \text{ \mu m}$ thickness). Actual plated thickness is measured by a Taly Step instrument. The plating solution is a commercially available silver cyanide-type bath.

The metallization system described above has been giving excellent results. It has been found to be unnecessary (and even undesirable) to sinter the metallization. It is interesting to note that, even when an insulating antireflection coating is not covering the silicon, silver plates only on the Ti-Pd film, not onto bare silicon.

Concern over possible corrosion problems when silver contacts are used with aluminum interconnects has prompted the investigation of other plated metals as a back-up to this process. Preliminary experiments with electroplated nickel have not been successful. Apparently, nickel deposits in previously undetected pin holes in the antireflection coating and, and if plating is continued long enough, a nickel film nearly completely covers the antireflection coating. Process variations are being studied to eliminate this phenomenon. Among these variations are more complete densification of the antireflection coating and changes in the nickel plating bath and plating conditions.

3.5 Cell Interconnections

The cell interconnection scheme to be demonstrated in this program is the ultrasonic welding of aluminum foils between cells, contacting both the dark side evaporated aluminum contact and the sun side electroplated silver (or nickel) contact.

Laboratory samples of metallized solar cells have been sent to three vendors of ultrasonic bonding equipment for recommendations on accomplishing ultrasonic bonding using existing equipment. One of these was not successful in bonding to the cells; the other two have made successful bonds to solar cells and have offered to cooperate in further improving the process.

Subsequent meetings with engineers of both companies resulted in recommendations for bonding parameters -- surface cleanliness, tool pressure, and ultrasonic frequency. Ultrasonic seam welding, in which the bonding tool is a wheel which rolls along the bond line, appears particularly well suited to high volume interconnection of cells in orthogonal arrays. Such a machine can produce continuous bonds at a linear rate up to 15 cm/sec whereas an ultrasonic spot welder requires approximately one second per bond.

Because manufacturers of incandescent lamps successfully solder lead wires to aluminum shells using automated equipment, interest has been expressed in this process for solar cells. Typically a Sn/Pb + 3% Cd solder is used with a urea-formaldehyde flux. The resulting bond is mechanically weak, suitable for lamps but probably not suitable for solar cells. Even though an automated system is used, only 3600 bonds per hour are produced. This number is not impressive when compared to alternative bonding methods.

3.6 Cell Processing

It was mentioned in Section 3.1 that cells produced using a standard process from web grown recently (with a nominal resistivity of 15 Ωcm) were different from those produced on web grown earlier (nominal resistivity of 5 Ωcm). This effect was explored in a more detailed experiment. The results for uncoated cells are shown in Table 4. In this experiment, the two web samples had resistivities of 5 Ωcm (web R-225-3.4) and 15 Ωcm (web J21-4.2). The cells in half of the samples for each web were chemically polished, removing 10 μm of silicon. In further processing, half of the CP samples were given a back surface field diffusion while the other half had only a phosphorus, front junction, diffusion. The sample experimental split was made on the non-polished samples.

In Table 4 Rows 1 and 3 (CP and not CP on 5 Ωcm web; with BSF) and Rows 5 and 7 (CP and not CP on 5 Ωcm web; no BSF) verify the data given in Section 3.1, that surface material removal is required to achieve maximum conversion efficiency in this web. Action of the BSF can also be observed in these data, as inferred from increases in J_{SC} and V_{OC} . The data in Rows 2 and 4 (CP and not CP on 15 Ωcm web; with BSF) and Rows 6 and 8 (CP and not CP on 15 Ωcm web; no BSF) are not as clear. The samples which do not have a BSF (Rows 6 and 8) show the normal behavior of the 5 Ωcm material, but the BSF samples (Rows 2 and 4) show an opposite effect. This experiment has been repeated several times and the additional data obtained show that CP treatment has little, if any, effect (good or

Table 4

Effect of Processing Variables on Dendritic Web Silicon (No AR Coating)

<u>ROW</u>	<u>SAMPLE</u>	<u>TREATMENT</u>	<u>I_{SC} (mA)</u>	<u>V_{OC} (V)</u>	<u>FF</u>	<u>η (%)</u>	<u>τ_{OCD} (μsec)</u>
1	W1	CP; BSF	21.4	.56	.73	9.3	6.0
2	W2	CP; BSF	21.9	.55	.69	8.8	15.0
3	W1	No CP; BSF	19.8	.49	.71	7.3	1.0
4	W2	No CP; BSF	22.4	.55	.72	9.5	19.0
5	W1	CP; No BSF	19.7	.52	.72	8.0	0.9
6	W2	CP; No BSF	20.5	.50	.71	7.6	1.5
7	W1	No CP; No BSF	19.5	.50	.72	7.3	.9
8	W2	No CP; No BSF	20.2	.49	.71	7.4	1.5

W1 = Web #1 R225-3.4 5 Ω cm; Thickness: Before 165 μ m, after 155 μ m

W2 = Web #2 J21-4.2 & 4.3 15 Ω cm; Thickness: Before 150 μ m, after 140 μ m

CP = Chemical polish in CP-4 solution

BSF = Back surface field

Numbers given are average for cells in group

bad) on the 15 Ω cm material. The data for one of these later runs are given in Section 3.7.

In this discussion, the two types of web have been categorized as 5 Ω cm and 15 Ω cm. At this point, it is not known if this effect is due to the resistivity of the crystal, or to some other variable associated with growth.

The table also shows that a BSF is operational in the 15 Ω cm web (Rows 2 and 4) and in the CP 5 Ω cm material (Row 1). The enhancement in V_{OC} is from 40 to 60 mV. The estimated diffusion lengths in these web cells are 288 μ m for Web #1 and 470 μ m for Web #2, using the method of Ref. 2, page 10.

3.7 Web Selection

Samples of dendritic web are being processed so that suitable crystals can be fabricated into 1.6 cm x 7.0 cm cells for module fabrication. Tables 5, 6 and 7 are printouts of cell results from the first three processing trials. Since this is the first time such printouts have been used in this program, an explanation will be given of the measurement method and printout.

The completed cells (no AR coating) are measured at AM1 illumination on specially designed equipment from which J_{SC} , V_{OC} and 5 points along the I-V curve can be determined. A computer program was developed on a previous project (JPL Contract 954331) which fits these data to a double exponential model.

The first of the 10 data columns gives the cell identification. Cells 1R* and 2R* are secondary standard cells used for light source calibration. Baseline cells, indicated by the designation "B", may or may not be included in a run. Web cells are designated using "R". A cell designator followed by ".*" indicates that some measured or derived parameter falls outside predetermined bounds and that the cell in question is not used for statistical evaluation of the run. J_{SC} is the short circuit current in mA, V_{OC} is the open circuit voltage in volts, JP is

Table 5

Comprehensive Cell Data on First Web Silicon Run

80420A WFFQUAL-1

RIEN3 5 / 4 / 78 AM1: PO=91.6044/CM12 NO AF COATING

ID	JSC	VOC	JP	LOG(JDD)	N	F*AO	FF	FFF	OCB
1R*	21.80	.553	19.38	-5.898	2.18	-.70	.710	9.35	.00
1P.*	20.43	.561	18.24	-5.808	2.28	-1.80	.735	9.19	4.00
2P	20.96	.572	19.09	-6.867	1.84	-.84	.752	9.84	6.50
4P	19.79	.564	18.01	-6.829	1.84	-1.00	.753	9.18	6.50
5P	20.53	.562	18.63	-6.606	1.91	-1.13	.751	9.46	8.50
1R	19.47	.517	17.31	-5.739	2.14	-1.52	.724	7.95	2.60
3R	17.87	.510	15.66	-5.259	2.43	-2.20	.709	7.05	1.60
4R	19.26	.521	17.07	-5.663	2.20	-1.48	.717	7.86	3.00
5R	20.96	.544	18.42	-5.531	2.36	-.85	.695	8.65	6.00
6R	19.79	.514	17.44	-5.481	2.27	-1.48	.710	7.88	4.00
7R	18.94	.511	16.80	-5.766	2.11	-1.23	.715	7.56	2.00
8R	19.89	.519	17.47	-5.355	2.37	-1.57	.705	7.95	3.90
9R	18.51	.507	16.37	-5.678	2.15	-1.23	.709	7.27	1.50
10R	21.38	.546	18.62	-5.094	2.66	-1.66	.694	8.85	15.00
11R	20.21	.540	18.06	-6.181	2.01	-.47	.714	8.50	5.00
12R	21.50	.534	17.99	-5.819	2.16	-1.23	.720	8.48	6.50
13R	21.70	.553	19.24	-5.528	2.39	-1.76	.724	9.49	14.00
14R	19.04	.514	16.71	-5.435	2.31	-1.30	.699	7.07	2.60
15R	17.34	.496	15.21	-5.622	2.15	-.66	.688	6.46	.60

AVERAGES: 80420A BASELINE

	20.43	.566	18.58	-6.767	1.86	-.99	.752	9.49	7.17
STD	.48	.004	.44	.115	.03	.12	.001	.27	.94

80420A WFFQUAL-1

	19.70	.523	17.31	-5.582	2.27	-1.33	.709	7.96	4.81
STD	1.30	.016	1.08	.257	.16	.44	.011	.76	4.32

PERCENT OF BASELINE

	96.5	92.5	93.2	117.5	122	65.2	94.3	83.8	67.1
STD%	8.8	3.6	8.2	5.3	11	65.1	1.6	10.7	77.1

Web Identification

1R	R-234-3.8	7R	J11-3.2	12R	J16-1.3
3R	J16-4.2	8R	J17-2.5	13R	J14-2.3
4R	J9-4.4	9R	J10-2.2	14R	J10-1.5
5R	J21-5.2	10R	J21-5.3	15R	J16-3.4
6R	J17-2.4	11R	J9-4.3		

Table 6

Detailed Data on Second Web Selection Run

80607 WEB QUAL 2-2

RIBN3 6 /20/78 AM1: PO=91.60MW/CM:2 NO AR COATING

ID	ISC	VOC	IP	LOG(10)	N	R	FF	EFF	OCD
2R*	21.90	.558	20.10	-7.359	1.64	-.56	.762	9.84	.00
2R	21.70	.536	18.95	-5.053	2.64	-2.09	.707	8.69	6.50
3R	21.50	.531	19.19	-5.892	2.10	-1.15	.725	8.75	6.50
4R X	21.50	.550	18.90	-5.282	2.54	-1.84	.712	8.90	7.80
5R	21.40	.550	18.98	-5.587	2.34	-1.62	.722	8.99	9.10
6R X	22.50	.562	19.67	-5.174	2.66	-1.59	.700	9.35	16.90
7R	22.70	.545	19.80	-5.156	2.59	-1.38	.694	9.08	10.40
8R.* X	22.00	.555	18.45	-4.071	3.84	-3.95	.674	8.70	10.40
10R	21.90	.544	19.49	-5.889	2.15	-.78	.713	8.98	6.50
11R	21.40	.535	18.93	-5.629	2.26	-1.10	.710	8.59	6.50
12R X	21.10	.554	18.69	-5.489	2.43	-1.92	.724	8.95	4.55
13R	18.60	.479	16.43	-5.606	2.06	-1.28	.709	6.68	1.90
17R	17.90	.472	15.64	-5.309	2.21	-1.48	.696	6.22	1.90
18R X	20.70	.511	18.34	-5.608	2.17	-1.39	.717	8.02	1.95
19R	17.80	.461	15.45	-5.185	2.24	-1.30	.684	5.93	1.30
20R	17.70	.462	15.36	-5.166	2.26	-1.40	.685	5.92	1.30
21R	22.70	.546	19.38	-4.464	3.23	-2.75	.684	8.97	11.70
22R	20.00	.510	17.49	-5.195	2.44	-1.78	.702	7.58	2.34

AVERAGES: 80607 BASELINE
NO BASELINE

	80607 WEB QUAL 2-2 FOR EDDIE SEMEN
	20.50 .522 18.05 -5.493 2.33 -1.43 .708 8.06 5.50
STD	1.69 .032 1.47 .507 .33 .54 .015 1.12 4.36

Web Identification

2R, 3R	RE1-1.2	12R, 13R	R215-1.2
4R, 5R	RE1-2.2	17R	R217-1.3
6R, 7R	RE3-6.3	18R, 19R, 20R	R242-3.4
9R, 10R, 11R	RE3-7.2	21R	RE3-6.3
		22R	RE3-7.3

Table 7

Detailed Data for Third Web Selection Run

80605 WEB QUAL 3 NO BASFLINES

FIEN3 6 /15/78 AM1: PG=91.60MM/CM12 NO AF COATING

ID	ISC	VOC	IF	LOG(10)	N	F	FF	FFF	OOD
2H*	21.90	.563	19.95	-6.780	1.84	-1.00	.756	9.86	.00
1F	18.20	.471	15.94	-5.365	2.17	-1.38	.698	6.33	1.00
2F	18.30	.477	16.14	-5.606	2.06	-1.15	.705	6.51	1.30
3F	18.50	.476	16.15	-5.216	2.28	-1.65	.697	6.49	1.30
4R	17.20	.469	15.25	-5.852	1.92	-.98	.710	6.06	1.30
5R	17.80	.476	15.52	-5.418	2.17	-.76	.681	6.10	1.30
9R	21.10	.536	18.64	-5.543	2.31	-1.34	.711	8.51	6.50
10R	22.30	.543	19.92	-5.899	2.14	-1.13	.726	9.30	19.50
11R	22.00	.540	19.31	-5.225	2.53	-1.82	.710	8.92	17.00
12R	22.50	.544	20.14	-6.008	2.08	-1.04	.728	9.43	19.50
13R	21.50	.537	19.45	-6.683	1.79	-.34	.732	8.93	10.40
14R	20.80	.501	18.26	-5.269	2.33	-1.70	.709	7.81	2.60
15R	21.00	.527	18.77	-6.000	2.04	-1.01	.725	8.48	6.50
16R	21.80	.537	20.02	-7.489	1.54	-.30	.757	9.37	15.60
17R	23.10	.555	21.08	-7.135	1.69	-.20	.744	10.08	22.80
18R	22.40	.538	20.00	-5.861	2.13	-1.23	.728	9.28	14.30
19R	22.30	.543	20.23	-6.729	1.79	-.52	.740	9.48	20.80
20R	23.40	.562	21.25	-6.826	1.81	-.33	.738	10.27	35.80
21R	22.90	.557	20.68	-6.544	1.90	-.46	.732	9.87	32.50
22R	20.70	.505	18.38	-5.653	2.13	-1.48	.723	7.99	3.30
23R	21.90	.519	20.02	-7.410	1.51	.14	.740	8.89	6.50
24R	21.60	.520	19.67	-7.065	1.61	-.19	.740	8.79	7.20

AVERAGES: 80605 BASFLINE
NO BASFLINE

80605 WEB QUAL 3 NO BASFLINES

	21.01	.521	18.80	-6.133	2.00	-.90	.723	8.42	11.76
STD	1.83	.030	1.85	.732	.27	.56	.018	1.33	10.22

Web Identification

1R, 2R, 3R	R238-1.3	13R, 14R, 15R	RE8-3.3
4R, 5R	R238-3.2	16R, 17R, 18R	RE9-3.3
9R	RE3-7.2	19R, 20R, 21R	RE10-2
10R, 11R, 12R	RE7-2	22R, 23R, 24R	J39-2.2

is the current at the peak power point, EFF is the conversion efficiency and OCD is the open circuit decay lifetime in μsec . The other columns LOG (JO) N, and R are parameters used in fitting the data to a standard model.

Although of no especial value here, the computer program also computes the parameter averages and standard deviations for the cells. If baseline cells are included in the run, the percentage ratio of web parameter to baseline parameter is also given.

The web identification is given below the table. R, J and RE refer to specific web growth furnaces.

The results shown in Tables 5, 6 and 7 generally track with the data given in Table 2. The acceptable samples generally show an enhanced value for VOC ($\approx 40\text{-}50\text{ mV}$) and OCD indicating an operational back surface field. However, this BSF is not fully functional since both V_{OC} and I_{SC} are still relatively low. The values of diffusion length (calculated as in Ref. 2, page 10) vary from $300\text{ }\mu\text{m}$ to $450\text{ }\mu\text{m}$.

The data in Table 6 (2nd selection run) give some further insight into the surface removal (chemical polishing treatment) discussed in Section 3.1. Cells 4R, 6R, 9R, 12R and 18R were chemically polished before fabrication to remove about $15\text{ }\mu\text{m}$ of silicon. (The cell designations are marked with X in Table 5.) The other cells in their specific group were processed unetched. Comparing the data on 4R with 5R; 6R with 7R and 9R with 10R and 11R, (all $15\text{ }\Omega\text{cm}$ crystals) we see no real difference between the CP and non-CP samples. The result differs from that of Section 3.1, where the CP treatment actually degraded the cell parameters. This effect must be investigated further.

The data on the $5\text{ }\Omega\text{cm}$ cells (Cf 12R with 13R and 18R with 19R, 20R) are completely consistent with our previous work. These crystals require some form of surface cleaning etching to achieve a maximum efficiency.

4. CONCLUSIONS

Experiments show that for 5 ohm cm web silicon produced to date, the formation of a boron doped back surface field region is not effective in improving cell efficiency unless about 10 μm of silicon is removed by CP-4 etching prior to front and back diffusions. On the other hand for 15 ohm cm web material, with otherwise identical web growth and cell processing, CP-4 etching has no significant effect. It is not currently known why such sensitivity should be related to web resistivity.

Use of a Silox^(R) reactor for doped oxide processing in the formation of BSF regions for baseline cells has given results comparable to those achieved with a cold wall open tube reactor. The Silox^(R) reactor is more conservative of materials and is better suited to processing of continuous ribbons of web silicon.

Deliberate doping of reagent grade POCl_3 (20 ppma Ti concentration) with Ti (using TiCl_4) to the 100 and 500 ppma levels causes no degradation of baseline cell performance. The glasses resulting from the diffusion operation, when analyzed using secondary ion mass spectroscopy, show lower ratios of Ti concentration than were established in the POCl_3 sources by doping. Two types of mechanisms appear to act to suppress introduction of electrically active Ti into the silicon wafers. Difference in vapor pressure of the two chlorides and in the oxidation mechanisms for the phosphorus and titanium species could reduce the actual amount of titanium incorporated in the glass as the Ti concentration in the POCl_3 source is increased.

The major implication for low cost cell processing is that it should be possible to acquire reagent grade POCl_3 with Ti concentrations specified and maintained below 500 ppm without undue cost. Cells produced using such material should not suffer performance degradation attributable to Ti.

Layers of TiO_2 for AR coating applications can be produced on ribbon material by pulling from a liquid metallorganic precursor at speeds up to 40 ft/min. Layers of about 600 Å thickness, adequate for cell coatings, can be produced by control of solution viscosity at speeds below 6 ft/min. At higher speeds, a low solids content (0.5% by weight TiO_2) solution gives relatively constant thickness for speeds of 15 to 40 ft/min. At a speed of 25 ft/min, the contribution of the AR coating step to selling price is estimated to be \$0.009/peak watt, using the JPL Interim Price Estimation Guidelines.

A metallization system of vacuum evaporated titanium/palladium followed by electroplated silver gives excellent results. Attempts to reduce cost by substitution of less expensive metals and elimination of vacuum deposition have not yet been successful. These efforts are continuing.

Ultrasonic bonding of foil interconnects to solar cells has shown technical feasibility and appears to be a low cost process. The quality of ultrasonic bonds is dependent upon the metal systems involved. Successful development of less expensive metal systems may necessitate a re-evaluation of ultrasonic bonds. Solder joints between aluminum interconnects and aluminum-metallized solar cells are technically feasible, but are unlikely to meet goals of cost and reliability.

5. PROGRAM STATUS

5.1 Present Status

As shown in Figure 2, the work on the program is on schedule. Development work on cell separation (Task 5) scheduled for the third quarter was not required since back surface laser scribing had been previously demonstrated to produce no degradation of cell performance, when properly done.* Effort on this task for the fourth quarter will be devoted to gathering yield statistics on scribing the cells required for module fabrication and to refining the economic analysis of this step.

5.2 Future Work

Fabrication of 1.6 cm x 7.0 cm cells on dendritic web silicon will be carried out for fabrication of a 30 cm square demonstration module. Statistical descriptions of cell performance parameters will be made for the proposed processing sequence. Several alternative implementations of the proposed process sequence will be analyzed for web cell processing cost contributions to prospects for achieving the goal of \$0.50/peak watt.

* Ref. 2. Section 3.3.

Milestones:

1. Approved Development Plan.
2. Preliminary Technical and Economic Evaluation Completed
3. Revised Process Sequence Established.
4. Process Verifications Completed.
5. Proof of Operation Completed.
6. Final Process Plans Established.
7. Material, Supply and Process Specifications and Process Procedures Delivered.

Figure 2
Approximate Task Schedule and Milestone Chart

6. REFERENCES

1. J. R. Szedon, R. B. Campbell, R. N. Ghoshtagore and B. E. Yoldas, First Quarterly Report DOE/JPL-954873-78-01 (April 1978).
2. J. R. Szedon, R. B. Campbell, R. N. Ghoshtagore, T. W. O'Keeffe and L. S. Scala, Second Quarterly Report DOE/JPL-954873-78-02 (May 1978).