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DOE/JPL/955624-80/2

SILICON DENDRITIC WEB MATERIAL PROCESS DEVELOPMENT

Second Quarterly Report

MASTER

By

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November 17, 1980

Work Performed Under Contract No. NAS-7-100-955624

Dist-343
NTIS-22

Westinghouse R&D Center
Pittsburgh, Pennsylvania

U.S. Department of Energy

Solar Energy

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DRL No. 126

DRD No. SE-5

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Distribution Categories UC-63 and UC-63b

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Contract 955624

This work was performed for the Jet Propulsion Laboratory,
California Institute of Technology under NASA Contract
for the U.S. Department of Energy.

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1. SUMMARY

The properties of the cells to be used in the first 30 cm by 60 cm module are given. The average efficiency was $12.4 \pm 0.8\%$. The highest efficiency measured was 14.2%. A satisfactory lamination has been made with polyvinyl butyral replacing ethylene vinyl acetate.

2. INTRODUCTION

This program addresses further process development on dendritic web silicon solar cells and modules, and the fabrication of demonstration solar modules.

In the previous program we had defined a process sequence for the fabrication of solar cells and modules, and had carried out development studies on specific key process steps. Using cost-effectiveness and cell performance as criteria, we selected the final process sequence, analyzed the results by SAMICS, and met the JPL cost objectives.

This program focusses on the development effort, particularly on the refinement of the interconnect process and the lamination of interconnected cells into a module.

The first development task is to determine the conditions required to achieve a high yield of ultrasonic bonds to thin dendritic web solar cells. The main emphasis is on ultrasonic seam bonding.

Ultrasonic bonding has several advantages as compared to solder for interconnecting, such as no corrosive flux, no material buildup and low material costs. The feasibility of ultrasonic bonding has been shown, but yields satisfactory for module fabrication have not yet been demonstrated. The primary factors affecting yield are poor quality bonds (low pull strength) or cell fracture. Thus, the emphasis in this phase of the present program is to determine conditions for reliable bonds while maintaining the cell integrity.

The current effort has indicated that with proper fixturing and bond parameters an acceptable yield is achievable.

The second development area is the lamination of interconnected cells into a module. Two laminate plastics have been evaluated -- ethylene vinyl acetate and polyvinyl butyral. In the lamination process, the cells are sandwiched between two layers of a plastic sheet. This assembly is then bonded to a superstrate and substrate using a pressure/temperature

cycle to form a package which is insensitive to environmental effects such as moisture and oxygen. Small modules (5" x 8") have been fabricated in this way using both EVA and PVB. This process is more cost effective than that used in our previous modules which used silicone potting, and in which a thermo-setting silicon resin was poured over the interconnected cells and formed an adhesive for mounting the glass superstrate.

Another major effort in this program is the design of a conceptual factory using the selected process sequence with dendritic web silicon as the input material. A cost analysis of this conceptual factory will be made to define overall costs as well as to determine which steps are the cost drivers.

3. TECHNICAL RESULTS

3.1 Cell Fabrication

During the period covered by this report a total of 133 cells of dimension 2.0cm x 10.0 cm were fabricated using single crystal silicon grown by the dendritic web process. The silicon web was p-type and the resistivity of the material used had an average and standard deviation of $5.4 \pm 1.9 \Omega \text{ cm}$ with a range of 2.3 to 11.9 $\Omega \text{ cm}$.

The length of the web strips was nominally 33 cm, with the processing of one such strip yielding three 2.0 cm x 10.0 cm cells. For the web that was used in this fabrication, the average and standard deviation of the thickness and width is $172 \pm 26 \mu\text{m}$ and $2.70 \pm 0.22 \text{ cm}$, respectively.

3.1.1 Description of Process

The process sequence is largely one that was developed earlier and is described in detail elsewhere.¹ Beginning with 33 cm long strips of web with surfaces as grown, the process steps may be summarized as follows:

1. Remove growth oxide and etch 10 μm from both sides of the web to eliminate possible molybdenum contamination;
2. Produce an n^+ layer on both sides by a POCl_3 diffusion at 850°C for 35 minutes;
3. Strip deposition oxide and protect the front side (sun side) with a Silox treatment;
4. Apply aluminum to the back side by a plasma spray;
5. Form a back surface layer of aluminum-silicon alloy by passing the strip through a vertical furnace whose hot zone is at 850°C with a nitrogen atmosphere;
6. Remove excess (i.e., unalloyed) aluminum from the back side;

7. Remove protective oxide layer from the front side;
8. Apply an anti-reflection coating by dipping and baking;
9. Apply a photoresist layer by dipping and baking;
10. Expose three 2 x 10 cm grid patterns on the front of the strip, expose the entire back, and develop the photoresist;
11. Define the grid pattern by etching the anti-reflection coating from the exposed areas;
12. Evaporate 500 Å of titanium, 300 Å of palladium, and 300 Å of silver over the entire front and back surfaces;
13. Form the grid structure on the front by dissolving the undeveloped photoresist in acetone, thereby rejecting the excess evaporated metal;
14. Electroplate copper to a thickness of approximately 10µm on the front grid pattern and on the back metal;
15. Sinter at 350°C for 15 minutes in a hydrogen atmosphere;
16. Define the cell border by laser scribing, then separate the cell from the surrounding material;
17. Test the 2 x 10 cm cell by a lighted I-V measurement.

3.1.2 Process Monitors

Several types of measurements have been carried out so that the results obtained in fabricating the cells can be compared with the results desired. The sheet resistance of the diffused n^+ region was measured as $(55 \pm 4) \Omega/\square$. This value is consistent with the formation of a thin ($\sim 0.3 \mu\text{m}$) n^+ layer which is required for efficient current collection.

After the aluminum was alloyed with the silicon to form a p^+ layer at the back surface, the impurity concentration profile was measured. The sample was beveled at the back surface to effectively expand the p^+ region. The spreading resistance was then measured at regularly spaced points along the beveled surface and from these measurements the acceptor

profile was constructed. Such measurements showed that the depth of the p-p⁺ junction varied over the range of 1 to 10 μm . Since small spherical particles comprise the source of aluminum in the plasma spray process, it is possible that there are small voids in the aluminum covering of the silicon. If this is so, the depth of the p-p⁺ junction would be expected to be somewhat non-uniform.

Shown in Fig. 1 is a typical back surface impurity profile with a surface concentration of $6 \times 10^{18}/\text{cm}^3$, a junction depth of approximately 5 μm and a base impurity concentration of $4 \times 10^{15}/\text{cm}^3$. Earlier theoretical considerations² suggest that such an arrangement of doping levels and p⁺ width will reduce the electron recombination velocity from 10^6 cm/sec at the back metal surface to an effective value of 10^2 cm/sec at the p-side of the p-p⁺ junction. This value is only slightly higher than the minimum value of approximately 70 cm/sec which results for p-p⁺ junction depths greater than 10 μm . Indications are, then, that the existing back surface field is serving to enhance cell performance.

The anti-reflection coating was characterized for five representative samples by an ellipsometer which employed a helium-neon laser. The thickness of the coating was found to be $900 \pm 40 \text{ \AA}$ and the index of refraction at the wavelength of the laser radiation ($6328 \text{ \AA}$) was measured as 2.04 ± 0.02 . Optimum values³ for an anti-reflection coating on silicon solar cells are a thickness of about 750 $\text{\AA}$ and an index of refraction of 2. Although some latitude is permitted when attempting to minimize the reflectivity over the entire solar spectrum, these measurements indicate the effectiveness of the anti-reflection coating can be increased if the thickness is reduced.

The thickness of the evaporated metal layers was monitored in situ by a crystal detector. The thickness of the electroplated copper layer was measured with a "Talystep" apparatus for six representative samples. Perhaps the most important region of the contact grid is the 1 mm square pad to which the cell interconnects are to be bonded. Measurements of the copper thickness on these pads fell in the range of 8 to 10 μm . A typical profile, shown in Fig. 2, is seen to give a surface roughness of approximately 0.4 μm . It was confirmed that good bonds could be made

Fig. 1—Impurity profile for the back surface field

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Fig. 2—"Talystep" recording of plated copper thickness across a contact pad

between the aluminum interconnect strips and the copper contact pads using the ultrasonic bonding technique discussed later in this report.

Sintering the processed web strips at 350°C for 15 minutes in hydrogen was done both to improve the adherence of the contact metal system and to provide a clean copper surface for ultrasonic bonding. In addition, the efficiency of the cells was found to improve somewhat with the sintering. Parameters for a test group of six 2 x 10 cm cells were measured before and after sintering and the efficiency of these cells was observed to increase by an average amount of 0.2%.

The border of the three cells on each web strip was scribed on the back of the strip by a laser. The depth of the laser scribe was examined in several cases with an optical microscope and found to be 40% to 50% of the thickness of the strip.

3.1.3 Results

A total of 133 2 cm x 10 cm cells were fabricated. The best cell had an efficiency (η) of 14.2%, with a short circuit current density (J_{sc}) of 29.4 mA/cm², an open-circuit voltage (V_{oc}) of 0.578V, and a fill factor (FF) of 0.765. These values were determined from a lighted I-V measurement using a simulated air mass 2 solar spectrum of 91.6 mW/cm² intensity.

Histograms of the measured efficiency, short circuit current density, open circuit voltage and fill factor for the entire 133 cell population are shown in Figs. 3, 4, 5, and 6. Excluding those cells whose parameter values deviate from the mean by more than 3 standard deviations, the results can be summarized as follows:

$$\begin{aligned}\eta &= (12.4 \pm 0.8) \% \quad (126 \text{ cells}) \\ J_{sc} &= (27.6 \pm 0.9) \text{ mA/cm}^2 \quad (125 \text{ cells}) \\ V_{oc} &= (0.548 \pm 0.014) \text{ V} \quad (132 \text{ cells}) \\ FF &= (0.763 \pm 0.017) \quad (123 \text{ cells})\end{aligned}$$

Analysis of the lighted I-V measurements for those cells which departed significantly (i.e., more than 3 standard deviations) from the norm usually indicated a defective junction in which excessive shunting

Curve 725319-A

Efficiency Histogram

133 2 cm x 10 cm Cells Fabricated

7 Cells with Efficiency Below 10.0 %

Average and Standard Deviation for Remaining 126 Cells:

$$\eta = (12.4 \pm 0.8) \%$$

Fig. 3—Efficiency histogram

Curve 725322-A

Fig. 4—Short circuit current density histogram

Curve 725321-A

Open Circuit Voltage Histogram

133 2 cm × 10 cm Cells Fabricated

1 Cell with V_{oc} Below 0.500 V

Average and Standard Deviation for Remaining 132 Cells:

$$V_{oc} = (0.548 \pm 0.014) \text{ V}$$

Fig. 5—Open circuit voltage histogram

Curve 725320-A

Fill Factor Histogram

133 2 cm × 10 cm Cells Fabricated

10 Cells with FF Below 0.680

Average and Standard Deviation for Remaining 123 Cells:

$FF = 0.763 \pm 0.017$

Fig. 6—Fill factor histogram

was present. This could happen if leakage paths at the edges of the cells were introduced by the laser scribing operation. Lapping the edges of these defective cells often reduced the shunting. In one case the efficiency increased dramatically from 8.17% to 13.5% after lapping.

3.1.4. Cells Selected for the First Module

Cells for the first 30 cm x 60 cm module were selected. The cells are to be arranged in three parallel strings, with each string being made up of 29 cells in series. In a series arrangement, the efficiency of the string tends to be limited by the cell with the lowest current-producing capability. The cells were grouped, therefore, according to their current density at the peak power point (J_p).

The four cells with the highest efficiency (14.0% or greater) were set aside for a closer examination at a later time. The remaining cells were arranged in order of decreasing J_p , as shown in Tables I-A, I-B, and I-C. The parameters of those 29 cells which will be used for the first (highest current) string are listed in Table I-A where J_p is shown to range from 27.5 to 25.9 mA/cm². Similarly, Table I-B gives the group of 29 cells which are meant to form the second (intermediate current) string with J_p ranging from 25.9 to 25.3 mA/cm². Finally, in Table I-C is given those cells which are to form the third (lowest current) string with J_p varying from 25.3 to 24.6 mA/cm².

Of course, for the entire module to operate effectively the voltage produced by the three strings must be reasonably well matched since these strings are to be connected in parallel. Some feeling for the extent to which these strings will be matched is given by summing the voltage at peak power (V_p) for all the cells within each of the three strings. When this is done the highest current string gives 13.3V, the intermediate current string gives 13.0V, while the lowest current string gives 13.0V. This good agreement indicates that when all three strings are connected in parallel, each of the strings will still be operating at nearly maximum efficiency.

Table I-A. Parameters for Cells Which Are to
Make Up the First String

Cell	J_p (mA/cm ²)	V_p (V)	J_{sc} (mA/cm ²)	V_{oc} (V)	FF	η (%)
1	27.53	.455	29.65	.553	.764	13.68
2	27.44	.462	29.65	.558	.766	13.83
3	27.04	.442	29.10	.533	.770	13.04
4	26.97	.458	29.00	.553	.770	13.48
5	26.96	.441	29.15	.532	.766	12.97
6	26.88	.470	29.00	.566	.770	13.79
7	26.76	.458	28.70	.551	.775	13.39
8	26.75	.459	28.90	.555	.766	13.42
9	26.74	.471	28.70	.563	.779	13.74
10	26.54	.455	28.45	.548	.774	13.18
11	26.54	.458	28.50	.550	.776	13.28
12	26.49	.455	28.35	.549	.774	13.15
13	26.35	.461	28.75	.559	.755	13.25
14	26.31	.465	28.35	.560	.771	13.37
15	26.26	.469	28.05	.563	.780	13.44
16	26.25	.473	28.35	.572	.765	13.54
17	26.25	.436	28.25	.526	.770	12.49
18	26.21	.454	28.05	.545	.779	13.00
19	26.19	.472	28.15	.563	.780	13.49
20	26.13	.473	28.60	.570	.758	13.48
21	26.06	.471	27.90	.569	.773	13.40
22	26.05	.425	28.65	.524	.737	12.08
23	26.05	.455	27.95	.551	.770	12.94
24	26.04	.445	27.60	.535	.785	12.66
25	26.02	.462	28.00	.560	.766	13.11
26	25.99	.475	27.75	.571	.779	13.48
27	25.97	.456	27.75	.548	.779	12.93
28	25.96	.457	27.80	.548	.778	12.94
29	25.92	.458	28.40	.556	.751	12.95

Table I-B. Parameters of Cells Which Are to
Make Up the Second String

Cell	J_p (mA/cm ²)	V_p (V)	J_{sc} (mA/cm ²)	V_{oc} (V)	FF	η (%)
30	25.87	.451	28.15	.547	.757	12.73
31	25.85	.451	28.30	.551	.747	12.72
32	25.85	.466	27.90	.560	.771	13.15
33	25.84	.452	27.85	.545	.769	12.75
34	25.83	.463	28.45	.563	.746	13.05
35	25.79	.455	27.75	.548	.771	12.80
36	25.79	.478	27.55	.571	.783	13.45
37	25.75	.449	27.30	.539	.785	12.61
38	25.75	.444	27.95	.538	.760	12.48
39	25.75	.451	27.30	.545	.781	12.69
40	25.73	.474	27.85	.570	.768	13.32
41	25.73	.447	27.70	.547	.759	12.55
42	25.71	.451	28.20	.549	.749	12.65
43	25.69	.465	27.90	.562	.762	13.05
44	25.65	.454	27.75	.551	.762	12.71
45	25.64	.406	27.75	.498	.754	11.38
46	25.60	.439	27.85	.533	.757	12.26
47	25.58	.447	27.50	.541	.769	12.50
48	25.55	.444	27.75	.543	.752	12.37
49	25.55	.426	27.85	.533	.734	11.90
50	25.54	.439	27.60	.531	.765	12.25
51	25.48	.460	27.50	.552	.772	12.79
52	25.47	.460	28.25	.567	.732	12.80
53	25.47	.427	27.60	.524	.752	11.87
54	25.38	.438	27.20	.524	.779	12.12
55	25.37	.438	27.20	.532	.768	12.13
56	25.36	.431	27.75	.531	.742	11.93
57	25.34	.447	27.10	.538	.776	12.36
58	25.30	.467	27.00	.558	.784	12.89

Table I-C. Parameters of Cells Which Are to
Make Up the Third String

Cell	J_p (mA/cm ²)	V_p (V)	J_{sc} (mA/cm ²)	V_{oc} (V)	FF	η (%)
59	25.29	.451	27.15	.541	.776	12.45
60	25.27	.450	27.25	.546	.764	12.41
61	25.24	.437	27.35	.529	.762	12.03
62	25.21	.444	27.10	.531	.777	12.21
63	25.21	.446	27.20	.540	.766	12.28
64	25.20	.438	27.30	.531	.761	12.04
65	25.19	.441	27.05	.533	.771	12.13
66	25.16	.460	27.10	.553	.773	12.65
67	25.13	.447	27.15	.538	.769	12.27
68	25.11	.442	27.05	.535	.766	12.11
69	25.02	.445	27.00	.541	.763	12.17
70	25.03	.444	27.25	.544	.749	12.12
71	25.02	.443	27.10	.540	.757	12.09
72	25.02	.461	27.50	.560	.749	12.60
73	25.01	.455	27.55	.554	.745	12.41
74	25.00	.459	27.20	.558	.756	12.52
75	24.99	.447	27.15	.544	.756	12.20
76	24.99	.444	26.90	.538	.767	12.12
77	24.98	.447	27.00	.540	.765	12.17
78	24.90	.441	27.25	.540	.746	11.98
79	24.88	.476	27.45	.567	.761	12.94
80	24.87	.454	27.20	.548	.757	12.33
81	24.86	.445	26.70	.538	.770	12.08
82	24.86	.450	26.80	.543	.769	12.21
83	24.84	.457	26.70	.552	.770	12.40
84	24.84	.447	27.30	.545	.746	12.12
85	24.78	.449	27.25	.553	.739	12.15
86	24.64	.444	26.55	.535	.770	11.94
87	24.63	.436	27.30	.531	.741	11.72

The fact that V_p is relatively independent of J_p for our cells is illustrated by the scatterplot of Fig. 7. There the range and distribution of V_p for each of the three strings is seen to be similar.

Fig. 7—Scatterplot of the voltage at peak power against the current at peak power for the cells chosen to comprise the first module

3.2 Ultrasonic Seam Bonding

3.2.1 Previous Status

In the First Quarterly Report the results of initial ultrasonic seam bonding tests are discussed. These tests were made using a Sonobond seam welder with special fixturing to hold the cell and interconnects firmly in place during the bonding process.

More than 200 bonds were made on both boron and aluminum back-surface-field cells. The boron BSF cells were included as baseline controls. A total of 182 bonds were pull tested (90° pull test) to determine the average strength.

The front contact structure of all cells was TiPdAg/electroplated Cu. The back contact of the boron BSF cells was also TiPdAg/electroplated Cu. About one half of the Al BSF cells were etched to remove excess back metal and remetalized with TiPdAg/electroplated Cu. With the other half of the Al BSF cells, the back was brushed to remove oxides and remetalized with 10 μ m of evaporated Al. (Previous work had shown that reliable ultrasonic bonds could not be made to the reacted Al on the back of the cell).

The general conclusions reached were:

1. Sintering of the contact structure was required to achieve maximum reproducibility of the ultrasonic bonds. The importance of cleanliness of both the contact metal and interconnect foil has been established.
2. The maximum bond pressure usable without cell breakage was 600 gmf. The highest strength bonds were made at 30 watts input power.
3. The average pull strength for the front TiPdAg/electroplated Cu contacts was about 85 gm.
4. The average bond strength for a back surface with TiPdAg/electroplated Cu was 75 gm.
5. On the samples where the back surface contact was 10 μ m of evaporated Al the average bond strength was 144 gm.

6. The ultimate strength of the Al foil interconnect was 200 gm. Thus, the ultrasonic bonds to the TiPdAg/electroplated Cu system were generally less than half the strength of the Al.
7. No cells were broken by the bonding itself during these tests which used 1 x 10 cm cells.

3.2.2 Current Status

Westinghouse has funded joint experiments with Kulicke and Soffa to determine the fixturing and bond parameters required to achieve a high yield of reliable bonds using both seam bonding and spot bonding. Some preliminary test with an ultrasonic-spot bonder were made at K&S using their Model 422 bonder. The ultrasonic tool face had an area of 45 x 20 mils. Aluminum BSF cells were used and bonds were made to the front surface. The front surface metal was as follows:

- Evaporated 400Å Titanium, 200Å Palladium, 200Å Silver followed by 8-12 μ m of electroplated copper
- After electroplating, the cells were sintered at 350°C for 30 minutes in nitrogen.
- Prior to bonding the copper surface was scrubbed with fine steel wool to remove an oxide layer formed during sintering.

Sixteen bonds (bond parameters ranged from 250 to 350 grams force at power levels from 9-12 watts) were made and then pull-tested. The results of the test yielded a range of bond strengths between 20 and 100 grams. Highest strengths were achieved with a force of 350 grams, a power of 11 to 12 watts and a 60 milli-second bond time (97 gram average for 2 bonds). The strengths are comparable to that achieved with the Sonobond seam welder. Several problems were encountered during these initial spot bonding experiments. They include:

- (1) ribbon sticking to tool face
- (2) cratering of silicon
- (3) ribbon damage
- (4) small bond areas

Based on these results it has been decided to defer further effort on ultrasonic spot bonding and continue development of the seam bonding concept for interconnecting demonstration modules.

A second group of 1 x 10 cm Al BSF cells were fabricated using an improved sintering process. These cells were sintered and cooled in hydrogen (350°C for 15 minutes) which produced a non-oxidized copper surface. Ultrasonic seam bonding tests were conducted to determine bond strengths of steel wool scrubbed and as sintered copper surfaces. The results are shown below:

(1)	steel wool scrub,	9 bonds pull tested (1 mil Al ribbon)
		average pull strength 81 grams, minimum 45 grams, maximum 125 grams, Std. Deviation 26 grams.
(2)	as sintered surface	8 bonds pull tested (1 mil Al ribbon)
		average pull strength 78 grams, minimum 25 grams, maximum 110 grams, Std. Deviation 29 grams.

Comparing these data with bonds made to as sintered copper from the first group of 1 x 10 cm Al BSF cells that were sintered in nitrogen shows

(3)	as sintered,	18 bonds tested (1 mil Al ribbon) average pull strength 41 grams, minimum 10 grams, maximum 80 grams, Std. Deviation 29

Since the bonding parameters were the same (1/4 in/sec, 500 grams, 30 watts) for each of these tests, it is concluded that steel wool scrubbing is not required for the hydrogen sintered cells.

One additional test was made with thicker aluminum ribbon (1.5 mil). The average pull strength for 6 bonds was 113 grams. This represents an increase in bond strength of 40 to 50% compared to 1 mil thick ribbon bonded under the same conditions (1/4 in/sec, 500 grams, 30 watts)

3.3 Fabrication of Small Test Modules

Based on the results described in the previous section and in the First Quarterly Report it has been concluded that ultrasonic seam bonding produces bonds of adequate strength with no significant cell loss because of breakage. The process therefore, appears satisfactory for module fabrication. Since these conclusions are based on bonding experiments with Al BSF test cells of 1 x 10 cm size, a further verification test was made with 2 x 10 cm cells. These cells are wider than the test cells but made by the same fabrication process. The Sonobond seam bonder and K&S fixture was set up at Westinghouse for this experiment. Prior to moving this equipment to Westinghouse a four-cell string was made with 1 x 10 cm cells at K&S. A photograph of this string is shown in Figure 8.

One mil aluminum interconnects were used. These ribbon pre-forms were ultrasonically seam bonded using the K&S fixture at 1/4 in/sec, 500 grams wheel pressure at 30 watts. No cell breakage is evident in these photographs but a visible track on each cell between bonding pads can be seen. This track is produced by the vibrating bonding wheel and is confined to the AR coating.

A second four-cell string was fabricated to test a method of reducing the damage to the AR coating and to evaluate equipment performance with 2 cm wide cells. (2 x 10 cm cells will be used for demonstration modules).

The damage to the AR coating made by the bonding wheel in the first four-cell string has been reduced by masking the areas between pads. A paper mask was positioned over the cell with cut-outs that only exposed the Al interconnect and bonding pad. In Fig. 9 is shown a photograph in which a paper mask was used in bonding a 1 x 10 cm test cell to an Al interconnect strip. Note that the mask served to protect the underlying AR coating. This can be seen by comparing Fig. 9 to Fig. 8 where no mask was used in the bonding. This masking approach appears to be a satisfactory solution until a better method can be implemented such as lifting the bonding wheel with cams or shutting off the ultrasonic power between bonding pads.

Figure 8. Photograph of an ultrasonically bonded string of four 1 x 10 cm test cells.

Figure 9. Photograph of an Al interconnect ultrasonically bonded to a 1 x 10 cm test cell using a paper mask.

four-cell string has been made using 2 x 10 cm cells and the base line bonding parameters. Some fixturing problems were also identified using the wider cells. The major problem appears to be the slots milled into the base of the fixture to provide vacuum hold-down. The edge of a 2 cm cell does not fully overlap the last row of slots. The cell edge is left unsupported and is subjected to a bending force when mechanically clamped. This problem was not detected until the stringing process was underway. Several cracks were produced in 2 of the cells as a result.

Electrical properties were measured for each of the cells before interconnection and for the series-connected four-cell string both before and after the string was encapsulated. These data are given in Table II and a photograph of the encapsulated string is shown in Fig. 10. Since the currents at peak power (J_p) of the individual cells were not well-matched, the efficiency of the string tends to be dominated by the cell with the lowest peak current. The electrical performance of the four-cell string before encapsulation is very close to the calculated performance using graphical methods. This indicates that the interconnect process and the cell cracks did not degrade performance. However, the drop in efficiency of the string after encapsulation is significant. This drop is attributed to an aggravation of the mechanical damage done to two of the cells during ultrasonic bonding, as indicated by a decrease in FF and J_{sc} . Some minor modifications are being made to the bonding fixture in an attempt to eliminate damage to the 2 cm wide cells.

TABLE II. Parameters of the Individual Cells, of the Four-Cell String before Encapsulation, and of the Four-Cell String after Encapsulation.

	J_p (mA/cm ²)	J_{sc} (mA/cm ²)	V_{cr} (V)	FF	η (%)
Cell 16-2	23.54	26.05	0.527	0.732	10.98
Cell 39-2	22.35	26.00	0.530	0.689	10.37
Cell 41-1	24.14	25.80	0.546	0.768	11.82
Cell 59-2	23.97	26.10	0.554	0.762	12.03
String (before Encapsulation)	23.00	25.05	2.080	0.740	10.52
String (after Encapsulation)	20.44	23.00	2.152	0.707	9.56

Figure 10. Photograph of an encapsulated string of four 2 x 10 cm cells.

It should be pointed out that a number of test encapsulations have been made without breakage, including two four-cell strings that had been interconnected by soldering. We feel, therefore, that it is not likely that the encapsulation process will introduce damage, but that it may amplify damage which had been done earlier.

3.4 Examination of Polyvinyl Butyral (PVB) as an Encapsulating Material.

A lamination fixture for 30 x 60 cm modules has been built and tested using ethylene vinyl acetate (EVA) as the encapsulating material for dendritic web prototype cells. The mechanical samples produced were free of bubbles or voids and no cell breakage was evident.

A similar mechanical sample was made using polyvinyl butyral (PVB). The same fixturing and vacuum lamination procedure was used. The maximum temperature was increased slightly (to 155°C) to aid in flowing the PVB. The materials and procedures used are outlined below.

- (1) Monsanto PVB sheets (SR10 Saflex .015 inch thick) dusted with sodium bicarbonate to prevent sticking (as received).
- (2) Wash PVB sheets in 120°F water and rinse with DI water to remove "soda" - air dry sheets by hanging with clips (N 12 hours).
- (3) Wash glass superstrate using a detergent scrub and rinse in DI H₂O followed by a final alcohol rinse - dry.
- (4) Prepare layup as follows:
  - (a) glass - superstrate (no primer required)
  - (b) PVB - 15 mils
  - (c) Dendritic web - prototype cells
  - (d) Crane glass - 5 mils
  - (e) PVB - 15 mils
  - (f) Korad 212 - 3 mils
  - (g) FEP - 3 mils
  - (h) Aluminum - 6 mils
  - (i) tape edges of layup with masking tape
- (5) The taped layup was placed in the 30 x 60 cm module fixture and laminated using the same heating and cooling cycle used for EVA as outlined in the First Quarterly Report, Contract 955624 (except for 155°C max. temp.)

Visually, the laminated sample (30 x 60 cm module size) was identical to those made with EVA (no cell cracking, voids or bubbles). The PVB was strongly bonded to the glass without the need for a primer coating.

A design for special heating and cooling plattens for the 30 x 60 cm module fixture has been made. Parts are on order for the cooling plates and fabrication was started for the heating plattens. With these components in operation, the total curing cycle from loading to unloading should be less than 1 hour compared to 5 hours at present. Additional tests will be made using the shorter cycle to verify performance.

3.5 Proposed Configuration for the Demonstration Modules

A preliminary design for the 30 x 60 cm modules has been made. The lamination is planned to be as follows:

- (1) Glass superstrate + primer coating
- (2) EVA sheet
- (3) Crane glass (optional)
- (4) Dendritic web solar cells
- (5) Crane glass
- (6) EVA sheet
- (7) Korad 212

Each module will contain a total of 87 2 x 10 cm cells divided into 3 series-connected strings of 29 cells each. The strings will be ultrasonically seam bonded using 1.5 mil thick aluminum ribbon preforms. End terminations will employ an aluminum strip ultrasonically bonded to the aluminum preforms at the ends of each string. The aluminum strip will be copper plated over part of its length so that it may be soldered to a connector. The three strings will be connected in parallel externally.

AMP Solar Module Connectors will be mounted on the back surface of the module at each end. The connector busbars will be soldered to the copper plated aluminum strips. The edges of the module will be sealed with a silicone rubber after lamination. Overall module size will be about 12.5 x 24.5 inches (31.8 x 62.2 cm). This allows for a 1/8 inch thick sealant bead on the four edges of the module.

4. CONCLUSIONS

1. The process sequence described for the fabrication of solar modules has been used to produce a number of 2 cm x 10 cm cells. These cells are suitable for fabrication into modules.
2. Although further work is required, the ultrasonic seam bonding method is feasible for interconnecting cells.
3. Polyvinyl butyral is a satisfactory laminate material for fabricating solar modules. No life data have been obtained.

5. REFERENCES

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