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ARRAY AUTOMATED ASSEMBLY TASK. LOW COST SILICON SOLAR
ARRAY PROJECT. PHASE 2

Quarterly Technical Report No. 6

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Work Performed Under Contract No. NAS-7-100-954865

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Chatsworth, California

MASTER

U.S. Department of Energy

Solar Energy

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PREFACE

The information presented in this report for the add-on study of Phase 2 of the Array Automated Assembly Task, represents work performed from February, 1979 through June, 1979, by Sensor Technology, Inc., located in Chatsworth, California. This program is directed by Sang S. Rhee. Principal contributors include Kimberly L. Allison, Gregory T. Jones, and Sanjeev Chitre.

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ABSTRACT

Work on the add-on study of Phase 2 of the Array Automated Assembly Task was conducted during this reporting period. This project covers the period from February 1979 through June 1979.

Three applications of the spray-on technique were investigated. The most effective spray-on boron back surface fields were produced at the drive-in temperature of 1000°C for the range of temperatures investigated. Of the three spray-on aluminum metallization techniques under consideration, two appear to be promising, and the third was shown to be unsuccessful. The smallest spray-on A.R. coating layer thickness available from our spray-on system at the present time was found to be $1000\text{\AA}$.

Work in the area of pulsed microwave heating for solar cell fabrication was initiated. A subcontractor was selected to develop an appropriate microwave system.

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INTRODUCTION

Seventeen process tasks were investigated by Sensor Technology, Inc. last year in Phase 2 of the Array Automated Assembly Task,⁽¹⁾ a DOE/JPL Low-Cost Solar Array (LSA) Project. A major effort was applied toward the analysis of solar cell and module process steps for throughput rate, cost effectiveness and reproducibility. The process sequence developed in this study was found to be in line with the objectives of the LSA program.

An extension of this contract was granted on February 22, 1979, for the purpose of investigating applications of the spray-on process technique developed in Phase 2 of the Array Automated Assembly Task for n^+ -p junction formation. The beneficial features of this technique include high wafer throughput, short processing time, high adaptability to large scale production and capability to perform a wide range of parametric variations. These features render the spray-on technique amenable to a number of applications. This program will apply the spray-on process technique to three areas, which include:

- (1) polymer dopant for back surface field formation,
- (2) aluminum spray-on metallization coating, and
- (3) anti-reflective coatings.

A second area selected for pursuit during the extension of this contract is microwave heating in solar cell fabrication. The solar cell process sequence requires a number of crucial wafer heating steps. Conventional thermal heating methods are plagued with low throughput rates, attendant high costs, and the potential to cause irreversible lifetime degradation at elevated temperatures.⁽²⁾ The utilization of microwave heating is expected to alleviate these undesirable process characteristics. In this program, the feasibility of using microwave heating for the following solar cell applications will be investigated: (1) sintering of applied metals, (2) drive-in of spray-on phosphorous polymer dopant, (3) drive-in of spray-on boron polymer dopant, and (4) annealing of ion implanted structures.

TECHNICAL DISCUSSION

A. POLYMER DOPANT FOR BACK SURFACE FIELD FORMATION

It has been well documented in the literature that the inclusion of an effective back surface field within the solar cell structure enhances open circuit voltage and short circuit current^(2,3,4). Back surface field formation with spray-on boron dopant is being investigated as an alternative, low-cost back surface field formation technique.

Spray-on boron back surface fields were demonstrated in earlier work⁽¹⁾. The main objective of the work performed during this reporting period was to assess the degree to which drive-in temperature variations influence the effectiveness of spray-on boron back surface fields.

Three batch tests were performed. All parameters were identical in each case, with the exception of the spray-on boron drive-in temperature. The set of processing steps utilized for each case followed the baseline fabrication sequence shown in Figure 1, with spray-on phosphorous, spray-on boron, and SiO AR coating. The I-V curves for Batches P-10 (1100°C), P-11 (1050°C), and P-12 (1000°C) are presented in Figures 2, 3, and 4, respectively.

FIGURE 1: Block diagram of solar cell process sequence.

FIGURE 2: Electrical performance curves for solar cells spray-on doped with boron and driven in at 1100°C for 25 minutes. The cells were tested under tungsten light at 100 mw/cm² and at 28°C.

FIGURE 3: Electrical performance curves for solar cells spray-on doped with boron and driven in at 1050°C for 25 minutes. The cells were tested under tungsten light at 100 mw/cm² and at 28°C.

FIGURE 4: Electrical performance curves for solar cells spray-on doped with boron and driven in at 1000°C for 25 minutes. The cells were tested under tungsten light at 100 mw/cm² and at 28°C.

Table 1. Electrical performance data for solar cells spray-on doped with boron and driven in at three different temperatures. Active area of the solar cells is 41.43 cm². The cells were tested under tungsten light at 100 mw/cm² and at 28°C.

BATCH	Isc	Voc	Ipp	Vpp	$\eta(\%)$	FF	$\frac{\Delta\eta}{\eta}(\%)$	$\frac{\Delta FF}{FF}(\%)$
P-10: Boron drive-in temperature was 1100°C for 25 minutes.								
High	1.31	.565	1.14	.390	10.73	.601	+6.87	-2.28
Low	1.14	.545	1.01	.380	9.26	.618	-7.77	+0.48
Wt.Ave.	1.23	.55	1.08	.385	10.04	.615		
P-11: Boron drive-in temperature was 1050°C for 25 minutes.								
High	1.31	.580	1.18	.420	11.96	.652	+6.31	+1.40
Low	1.22	.565	1.01	.425	10.36	.623	-7.91	-3.11
Wt.Ave.	1.26	.575	1.11	.420	11.25	.643		
P-12: Boron drive-in temperature was 1000°C for 25 minutes.								
High	1.32	.585	1.18	.445	12.67	.680	+4.71	+2.56
Low	1.28	.570	1.12	.415	11.22	.637	-7.27	-3.92
Wt.Ave.	1.30	.580	1.15	.435	12.10	.663		

It is clear from the table that Batch P-12 (1000°C) has the highest average efficiency and fill factor of the three batches. In addition, Batch P-12 manifests the highest average short circuit current and open circuit voltage of the three batches.

Since enhanced open circuit voltage and short circuit current is characteristic of an effective back surface field, it appears that a low drive-in temperature (1000°C) is conducive for spray-on boron back surface fields.

B. ALUMINUM SPRAY-ON METALLIZATION STUDY

A low cost spray-on technique for applying aluminum to the back surface of solar cells is undergoing investigation. Preliminary experimentation in this area involved spraying a binder solution onto the silicon wafer back surface, followed by spraying powdered aluminum. The aluminum oxide particles produced by rapid oxidation of powdered aluminum in the spray-on system exploded. To avoid this situation in subsequent experiments, aluminum slurry will be used in place of the powdered aluminum. Two aluminum slurry spray-on methods were formulated to demonstrate the feasibility of the spray-on aluminum technique. The first method involves the use of a proximity sprayer which simultaneously sprays on aluminum slurry and binder solution through separated nozzles. Initial experiments resulted in uniformity problems which will be investigated further next quarter. The second technique to be considered next quarter will utilize an aluminum/binder slurry which will be sprayed through one nozzle.

The existing spray-on system at Sensor Technology, Inc., requires several equipment modifications in order to perform the necessary experiments. These equipment

modifications include the addition of a metallizing spray booth, which will be located ahead of the present spray chamber, and an extension of the conveyor.

The operation of this revised system requires manual removal of the pallet from the present booth where the binder solution is applied, and subsequent placement of the pallet ahead of the new booth where the metal will be applied. The completion of all required equipment modifications will take place next quarter.

C. SPRAY-ON ANTI-REFLECTIVE COATING STUDY

1. BACKGROUND

The development of low-cost, high efficiency solar cells is facilitated by the use of a low-cost technique for applying anti-reflective coatings. One promising method involves spraying on anti-reflective coatings. In order to ensure the success of this method, the spray-on system must be capable of consistently spraying the A.R. coating to a designated thickness.

The anti-reflective coating thickness, which provides minimal reflection losses can be, in principle, theoretically computed. However, for our purposes, a number of simplifying assumptions were made in order to obtain an approximate value for the AR coating layer thickness which leads to minimal reflection losses. These assumptions include:

- (1) normal incident light on a flat wafer surface,
- (2) monochromatic incident light, and (3) no absorption loss in the A.R. coating layer.

A discussion of the procedure used to compute the A.R. coating layer thickness which minimizes reflection losses is presented below.

For a single layer A.R. coating at a single wavelength, λ , the reflectance, R , is given by the following expression:

$$R = |r|^2 = \left| \frac{(n_0 - n) \cos k_1 l_1 - i(n n_0 / n_1 - n_1) \sin k_1 l_1}{(n_0 + n) \cos k_1 l_1 - i(n_1 + n n_0 / n_1) \sin k_1 l_1} \right|^2 \quad (1)$$

n_0 = refractive index of the incident medium

n = refractive index of the transmitting medium

n_1 = refractive index of the A.R. coating

$k_1 = 2\pi n_1 / \lambda$

l_1 = thickness of A.R. coating

If the optical thickness of the A.R. coating $n_1 l_1$ is a quarter wavelength, then $k_1 l_1 = \pi/2$ and the reflectance for a quarter wavelength film becomes:

$$R = |r|^2 = \left(\frac{n n_0 - n_1^2}{n n_0 + n_1^2} \right)^2 \quad (2)$$

It is clear that the reflectance is zero if $n_1 = (n n_0)^{1/2}$ for $l_1 n_1 = \lambda/4$.

The anti-reflective coating, which was studied during this reporting period was titaniumsilica "C". The thickness of titaniumsilica "C" A.R. coating with refractive index n_1 equal to 1.95 that minimizes reflection losses was computed as follows:

$$l_1 = \frac{\lambda}{4 n_1} = \frac{6000 \text{Å}}{4(1.95)} = 769 \text{Å}$$

This thickness corresponds to a quarter wavelength for photons near the middle of the usable solar spectrum, i.e. $\lambda = 6000\text{\AA}$. The reflection loss at this thickness was computed with the aid of Equation 2. The reflection loss amounts to 0.064%, for this case. If an A.R. coating with a refractive index of 2.0 had been used instead of titaniumsilica "C", the reflectivity would be zero.

2. EXPERIMENTAL WORK

Initial experimentation in the area of spray-on A.R. coatings focussed on achieving a titaniumsilica "C" A.R. coating layer thickness approaching the values of $769\text{\AA}$. Several preliminary test runs indicated that our present spray-on system was not capable of achieving titaniumsilica "C" A.R. coating layer thicknesses below $1000\text{\AA}$. Nevertheless, two batch tests were performed to determine the viability of the spray-on A.R. coating technique.

Both solar cell batches were processed with the fabrication sequence shown in Figure 1. Following SiO_2 removal in each case, the electrical performances of the solar cells were measured. Titaniumsilica "C" A.R. coating was then sprayed onto Batch (T-100) to a thickness of $1500\text{\AA}$, and sprayed onto Batch (T-101) to a thickness of $1000\text{\AA}$. The electrical performances of both batch tests were then remeasured.

Upon comparison of the electrical performance results before and after the spray-on A.R. coating application in Table 2, it can be seen that the average short circuit current and average efficiency improved 11.8% and 10.18% for Batch T-100 (1500Å), and 13% and 10.8% for Batch T-101 (1000Å). Clearly, the smallest A.R. coating layer thickness (1000Å) led to the largest improvements in average short circuit current and average efficiency. Equipment modifications of our spray-on system are currently underway to achieve titaniumsilica "C" A.R. coating layer thicknesses approaching the value of 769Å.

Table 2: Solar Cell Electrical Performance Versus Coating Thickness For Spray On Titanium-silica "C".

BATCH	I _{SC} (a)	V _{OC} (v)	I _{PP} (a)	V _{PP} (v)	η(%)	FF
T-100 No A.R. coating (SiO ₂ removed).						
1	1.12	.570	1.03	.425	10.57	.686
2	1.125	.569	1.02	.450	11.087	.717
3	1.06	.570	.92	.435	9.667	.662
4	1.14	.565	1.05	.425	10.779	.693
5	1.11	.570	.97	.425	9.958	.652
Ave.	1.11	.569	1.00	.432	10.41	.682
T-100 Titaniumsilica "C" A.R. coating, 1500Å thickness.						
1	1.25	.570	1.14	.430	11.84	.688
2	1.19	.573	1.10	.443	11.77	.715
3	1.23	.575	1.01	.430	10.49	.614
4	1.29	.570	1.16	.430	12.04	.678
5	1.25	.570	1.08	.430	11.23	.652
Ave.	1.24	.572	1.10	.433	11.47	.669

Table 2: (Continued)

BATCH	I _{SC} (a)	V _{OC} (v)	I _{PP} (a)	V _{PP} (v)	η (%)	FF
T-101 No A.R. coating (SiO ₂ removed).						
1	1.12	.565	1.01	.445	10.856	.71
2	1.13	.570	.98	.450	10.648	.685
3	1.13	.575	.95	.450	10.32	.658
4	1.16	.565	1.02	.440	10.83	.685
Ave.	1.135	.569	.99	.446	10.66	.685
T-101 Titaniumsilica "C" A.R. coating 1000A thickness.						
1	1.25	.570	1.10	.430	11.425	.664
2	1.29	.575	1.12	.450	12.17	.679
3	1.29	.575	1.10	.440	11.68	.653
4	1.30	.570	1.14	.435	11.97	.669
Ave.	1.28	.573	1.115	.439	11.81	.666

D. PULSED MICROWAVE HEATING FOR SOLAR CELL FABRICATION

An investigation of the microwave field was conducted in order to obtain a suitable background in this area. On the basis of the information obtained from this study, several pulsed microwave heating applications for solar cell fabrication were identified and are listed below:

- (1) sintering of applied metals
- (2) junction formation using spray-on polymer dopants
- (3) back surface field formation
- (4) annealing of ion implanted structures

The performance of the above tasks depends on the availability of an appropriate microwave heating device. Conventional microwave ovens were found to be unsuitable for solar cell heating applications. A novel approach was needed. Cober Electronics of Stamford, Connecticut, was selected as a subcontractor to perform the following activities:

1. Development of an appropriate microwave heating device with the capability of performing the following parametric variations:

- a. temperature;
 - b. depth of pulsed microwave penetration;
 - c. rate and duration of pulsed microwaves; and
 - d. microwave power.
2. Detailed process specifications including pulsed microwave machine operational parameters and allowable attendant variances which conform to parameter specifications supplied by Sensor Technology, Inc.

CONCLUSIONS

Work performed this quarter on the spray-on metallization task led to one conclusion. Of the three spray-on aluminum metallization techniques under consideration, one technique was demonstrated to be unfeasible. This technique involved spraying a binder solution onto the silicon wafer surface, followed by spraying powdered aluminum. It was found that the aluminum oxide particles produced by rapid oxidation of the powdered aluminum in the spray-on system exploded, thus rendering this technique completely untenable for our purposes.

RECOMMENDATIONS

There are no recommendations to report at the present time.

PROGRESS SUMMARY AND PROGRAM PLAN

The progress summary and program plan for the add-on study of Phase 2 of the Array Automated Assembly Program is presented in the Milestone Chart in Table 3.

Table 3:

MILESTONE SCHEDULE DIAGRAM
Phase 2 Array Automated Assembly Task
Contract No. JPL 954865, Mod. 4 & Mod. 6

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Effective from May, 1979

Second Modification

TASK	1979								1980			
	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
A. SPRAY-ON STUDY												
1) Back Surface Field Formation												
2) Metallization Coating												
3) Anti-reflective Coating												
4) Other Coatings												
B. MICROWAVE PULSE STUDY												
1) Source Evaluation & Subcontract												
2) Study Phase												
(a) Junction Formation												
(b) Back Surface Field Formation												
(c) Sintering												
(d) Annealing after ion implantation												
3) Measurement of effectiveness in the four applications												
4) Cell and process evaluation in the four applications												
C. PROCESS COST ANALYSIS (SAMICS)												

Table 3:

MILESTONE SCHEDULE DIAGRAM

Cont'd

TASK	1979								1980			
	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
D. SAMPLE DELIVERY												
E. PROCESS SPECIFICATIONS												
F. REPORTS												
1) Monthly Financial Reports	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲
2) Monthly Technical Reports	▲		▲	▲		▲	▲		▲	▲		
3) Quarterly Reports		●			○			○				
4) Final Report (Draft)											□	
5) Final Report												□

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