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LOW COST SOLAR ARRAY PROJECT

CELL AND MODULE FORMATION RESEARCH AREA

PROCESS RESEARCH OF NON-CZ SILICON MATERIAL

QUARTERLY REPORT NO. 4

December 1, 1982 to February 28, 1983

CONTRACT NO. 955909

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

Advanced Energy Systems Division
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LOW COST SOLAR ARRAY PROJECT
Cell and Module Formation Research Area

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Approved:

C. M. Rose, Manager
Photovoltaic Pilot Operations

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I. CONTRACT GOALS AND OBJECTIVES

The primary objective of this contract is to investigate high-risk, high-payoff research areas associated with the Westinghouse process for producing photovoltaic modules using non-CZ sheet material. All investigations are being performed using dendritic web silicon, but all processes under study are directly applicable to other ribbon forms of sheet material. The contract is separated into the following tasks.

A. Liquid Junction Technical Feasibility Study

The objective of this task is to determine the technical feasibility of forming front and back junctions in non-CZ silicon using liquid dopant techniques. Numerous commercially available liquid phosphorus and boron dopant solutions are under investigation. Temperature-time profiles to achieve N^+ and P^+ sheet resistivities of 60 ±10 and 40 ±10 ohms per square, respectively, have been established; and verification runs using liquid boron for the back junction have been made.

B. Liquid Diffusion Mask Feasibility Study

The objective of this task is to determine the technical feasibility of forming a liquid applied diffusion mask to replace the more costly chemical vapor deposited SiO_2 diffusion mask. Parameters under investigation include liquid applied diffusion masks procured from various vendors, temperature-time profiles for baking liquid masks, film thickness relationship with masking capabilities, identification of etching solutions, process parameters for post-diffusion removal of masks, and methods of liquid mask application.

C. AR, PR Meniscus Coating Application Studies

The original objective of this task was to determine the technical feasibility of applying liquid antireflective (AR) and photoresist (PR) solutions using meniscus coating equipment. Film thickness relationships with antireflective capabilities have been investigated. The AR films formed have been shown to have uniform thickness along the web and possess the required antireflective properties. Present plans are to use the meniscus coater to apply liquid phosphorus to form the front N^+P junction.

D. Ion Implantation Compatibility/Feasibility Study

In this task, the feasibility of producing uniform high efficiency solar cells from non-CZ silicon using ion implantation junction formation techniques will be established. This task will build upon existing information on ion implantation of non-CZ material from other programs and will include:

- An investigation of process variations between processing ion implanted cells and processing gaseous diffused cells using a standard gaseous diffusion process as a baseline;

- Comparison and evaluation of cell efficiencies of ion implanted cells with gaseous diffused cells using a standard gaseous diffusion process as a baseline; and an

- Evaluation of ion implantation parameters such as ion species, energy and dose for front and back junctions, ion implantation angle, annealing method, annealing time and temperature, surface treatment of input non-CZ material, and input non-CZ characteristics including resistivity.

E. Cost Analyses

In this task, SAMICS methodology will be used to quantify production cost improvements associated with process improvements under investigation.

II. SUMMARY

This report describes work performed on JPL Contract No. 955909, "Process Research of Non-CZ Silicon Material," during the quarterly period from December 1, 1982, to February 28, 1983. Technical work in this time period emphasized investigations for liquid diffusion masks and liquid dopants to replace the more expensive CVD SiO_2 mask and gaseous diffusion processes. The latter were specified in the Westinghouse baseline process sequence for producing solar cells from dendritic web silicon. JPL contract funds are being used only to define experiments, evaluate data, and report results relative to this task. All technical and material costs associated with this work are being borne by Westinghouse.

In addition to the liquid dopant studies, silicon pellets have been prepared in the silicon shot tower; and solar cells have been fabricated using web grown where the pellets were used as a replenishment material.

During this period, a number of verification runs were made using the boron dopant [illegible] liquid diffusion mask materials from Diffusion Technology. The aver[illegible] [illegible]ls produced in these runs was 13%.

Experiments were [illegible]ried out to determine the relationship of sheet resistivity, temperature, gas flows, and gas composition for the diffusion of the P-8 liquid phosphorus solution supplied by Diffusion Technology. The liquid was applied using the squeegee applicator. Cells produced had a wide range of efficiencies, mainly due to problems in application of the liquid diffusant. These problems should be alleviated with the use of the meniscus coater which was purchased with Westinghouse capital funds and was delivered to AESD near the end of this reporting period.

A number of cells produced in the past few months (about 11%) with very low efficiencies have been analyzed. The major problem was found to be contamination of the front N^+P junction with boron dopant. Again, the most likely source of the problem is occasional non-uniform (manual) application of liquid SiO_2 to the web surface.

An initial delivery of dendritic web was made to JPL for transmittal to Spire Corporation for ion implantation studies.

A number of successful shot tower runs have been made. Pellets produced in these runs have been used as replenishment material in dendritic web growth furnaces being operated at AESD. Solar cells processed from web grown from Si shot material have been evaluated, and results have qualified the use of the material produced in the shot tower for web furnace feed stock.

An abstract and extended abstract of a joint paper between Westinghouse and JPL on liquid dopants were approved by JPL and submitted to the Electrochemical Society for presentation at their meeting in May 1983.

III. TECHNICAL PROGRESS

A. Liquid Boron Verification Runs

Over sixty photovoltaic cell production runs were completed using the Westinghouse baseline process sequence modified to include liquid SiO_2 diffusion masks and liquid boron dopant. The runs were made in the period December 6, 1982, through January 6, 1983; and results were analyzed during this reporting period. The sequence used to form junctions in these cells is given in Table 1. In all of these process runs, liquid SiO_2 and boron dopants obtained from Diffusion Technology were used. The gas composition used for the liquid boron drive (Step 9 in Table 1) was 80% N_2 and 20% O_2 closely simulating open air.

Table 2 shows the average efficiency of cells produced in these verification runs. Cells produced were of the three standard sizes normally fabricated on the Westinghouse Pre-Pilot Facility - 1.6 cm x 9.8 cm, 2.0 cm x 9.8 cm, and 2.5 cm x 9.8 cm. The overall data also include results from experimental runs (cleaning procedures, etc.) which were made during this period.

The overall average of 13% is significantly higher than the 12.6% average efficiency of cells processed by the baseline sequence as reported in Monthly Report #23 (December 6, 1982). However, a one-to-one comparison of the liquid process (using the Diffusion Technology liquids) with the baseline process is not possible since no baseline sequence runs were made during the period reported on here.

B. Formation of Front N^+P Junctions using Liquid Phosphorus

The use of a liquid boron dopant for the formation of the back surface P^+P junction has been verified and is now part of the Westinghouse baseline processing sequence for fabricating solar cells from dendritic web silicon. The use of this liquid process for back junction formation results in a considerable saving of processing time.

However, an even greater saving of time is possible if a liquid process can be developed for the front N^+P junction. Studies to determine feasibility of

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TABLE 1

PROCESS SEQUENCE FOR FABRICATION OF SOLAR CELLS
USING LIQUID BORON AND LIQUID DIFFUSION MASKS

1. Raw web cleaning (including the hot H_2SO_4 treatment).
2. Pre-diffusion cleaning (standard chelating).
3. Paint on liquid SiO_2 on designated N^+ side using a sponge-squeegee.
4. Dry under heat lamp for 5 minutes (about 80°C).
5. Paint on liquid boron dopant on designated P^+ side using a sponge-squeegee.
6. Dry under heat lamp for 5 minutes (about 80°C).
7. Load strips in boat with SiO_2 side facing SiO_2 side and P^+ side facing P^+ side. Pre-bake in oven for 15 minutes at 200°C.
8. Place loaded boat in front end of diffusion furnace and bake strips for 5 minutes at approximately 300°C.
9. Move boat into furnace and diffuse for 30 minutes at 980°C. Slow cool furnace to 700°C at 3°C/minute.
10. Strip oxides in 2:1 H_2O:HF.
11. Repeat Step 2.
12. Paint on liquid SiO_2 on boron diffused side using a sponge-squeegee.
13. Repeat Step 4.
14. Load strips into boat with SiO_2 side facing SiO_2 side.
15. Place boat into front end of $POCl_3$ diffusion tube and bake strips for approximately 300°C.
16. Move boat into furnace and diffuse in gaseous $POCl_3$ for 20 minutes at 850°C (baseline conditions). Slow cool furnace to 700°C for 3°C/minute.
17. Strip oxides and complete baseline process.

TABLE 2

LIQUID DOPANT/LIQUID DIFFUSION MASK TEST RUNS
PERFORMED DECEMBER 6, 1982 THROUGH JANUARY 6, 1983

No. of Cells	Av. Efficiency (%)
3054	13.0

This data does not include 396 cells produced with less than 10% efficiency. Data from these reject cells are discussed separately in this report.

such a process were initiated in December and are continuing. Initial experiments using phosphorus doped liquids from various vendors when applied using the sponge-squeegee method resulted in badly stained front surfaces, making the surfaces unsuitable for cell fabrication. Tests with the "CAVEX" meniscus coater and conducted by the vendor indicated that with the more uniform layers of the phosphorus dopant obtainable with this unit, the staining could be significantly reduced. On this basis, a meniscus coater was placed on order using Westinghouse capital funds.

While awaiting delivery of the unit, the liquid front junction studies were restricted to the determination of times, temperatures, and gas compositions which resulted in acceptable sheet resistivities. In these studies, it was found that the P-8 liquid phosphorus solution from Diffusion Technology produced the least amount of front surface staining. This material has been used for the scoping work in cell processing parameters prior to delivery of the meniscus coater. The procedure followed for these experiments is outlined in Table 3. Initially, strips were painted with liquid phosphorus solution and diffused at 900°C to 950°C for 20 minutes and 30 minutes in varying $N_2 + O_2$ ambients. It was found that oxygen concentration in the $N_2 + O_2$ mixture was extremely important in achieving the sheet resistivity (ρ_s) desired for the N^+P junction. In 100% O_2 ambient, strips diffused at 900°C for 30 minutes yielded high sheet resistivities which were of the order of 100 Ω/□ . Table 4 summarizes the results of the various experiments. It is instructive to note that the N_2 rich mixture yielded sheet resistivities of the order of 40-50 Ω/□ which is slightly less than the desired value based on the baseline gaseous diffusion process. (The optimum sheet resistivity for gaseous $POCl_3$ diffusion is 50-70 Ω/□.)

It was noted in these tests that in a number of cases there was a wide variation of resistivity along the length of the web, with some areas being as high as 300-400 Ω/□. The reason for this variability is not known but is probably related to a non-uniform coating of the phosphorus liquid, leading to variable diffusant source concentrations on the surface. Some of the strips from these experiments have been processed through the baseline process and made into

TABLE 3

PROCESS SEQUENCE FOR FABRICATION OF SOLAR CELLS
USING LIQUID DOPANTS AND LIQUID DIFFUSION MASKS

1. Raw web cleaning (including the hot H_2SO_4 treatment).
2. Pre-diffusion cleaning (standard chelating).
3. Paint on liquid SiO_2 on designated N^+ side using a sponge-squeegee.
4. Dry under heat lamp for 5 minutes (about 80°C).
5. Paint on liquid boron dopant on designated P^+ side using a sponge-squeegee.
6. Dry under heat lamp for 5 minutes (about 80°C).
7. Load strips in boat with SiO_2 side facing SiO_2 side and P^+ side facing P^+ side. Pre-bake in oven for 15 minutes at 200°C.
8. Place loaded boat in front end of diffusion furnace and bake strips for 5 minutes at approximately 300°C.
9. Move boat into furnace and diffuse for 30 minutes at 980°C. Slow cool furnace to 700°C at 3°C/minute.
10. Strip oxides in 2:1 H_2O:HF.
11. Repeat Step 2.
12. Paint on liquid SiO_2 on boron diffused side using a sponge-squeegee.
13. Repeat Step 4.
14. Paint on liquid phosphorus on designated N^+ side using a sponge-squeegee.
15. Dry under heat lamp for 5 minutes (about 80°C).
16. Load strips in boat with SiO_2 side facing SiO_2 side and P^+ side facing P^+ side. Pre-bake in oven for 15 minutes at 200°C.
17. Load boat into furnace and diffuse for 30 minutes at 900°C. Slow cool furnace to 700°C at 3°C/minute.
18. Strip oxides and complete baseline process.

TABLE 4

DATA ON LIQUID PHOSPHORUS DOPED SILICON DENDRITIC WEB STRIPS

Run #	Diffusion Temp./Time	Gas Mixture	ρ_s ($\Omega/\square$)	Remarks
1	900°C/30 min.	100% O_2	$\geq$100	Surface Clean after Stripping
2	950°C/30 min	50% O_2 50% N_2	7-8	Surface Clean after Stripping
3	900°C/30 min	50% O_2 50% N_2	25-28	Surface Clean after Stripping
4	900°C/30 min	30% O_2 70% N_2	26-41	Surface Clean after Stripping
5	900°C/30 min	20% O_2 80% N_2	33-50	Surface Clean after Stripping
6	900°C/30 min	5% O_2 95% N_2	21-27	Surface Clean after Stripping
7	900°C/20 min	5% O_2 95% N_2	24-29	Surface Clean after Stripping

cells. The efficiencies on these cells ranged from 10 to 14%. Highest efficiencies were obtained on strips with ρ_s ranging from 25 to 50 Ω/□. Several other runs have been carried out using the 900°C/30 min. drive in 80% N_2 - 20% O_2 diffusion conditions.

In the first such cell processing run, 9 strips of web were coated with the P-8 solution and diffused at 900°C for 30 minutes. After this treatment, the same variability of sheet resistivity was noted on the diffused strips. Twenty-two cells from these strips had an average efficiency of 11.2 ±1.5% with a maximum efficiency of 13 4%, considerably lower than cells produced in the baseline process sequence.

Before another test could be made, the phosphorus liquid gelled; and it was difficult to apply it to the web with any degree of uniformity. The material was five weeks old at this point; and when contacted, the vendor stated the solution had a shelf life of four weeks which could be even shorter when exposed to air. This short lifetime must be a concern in any production process and in the use of the meniscus coater where a large volume of material (≈1 liter) is required for operation but where the total solution usage is low. During the next period, work will be initiated with various vendors to resolve this problem.

Since no other phosphorus liquid was immediately available, one further test was carried out with this thickened liquid.

Web strips were selected from a processing run after boron diffusion, coated with P-8, and diffused at 890°C for 30 minutes. The furnace ambient was 80% N_2 - 20% O_2. The remainder of the strips were diffused in gaseous $POCl_3$. After the front junction diffusion, all strips were again merged into one run and finished processed as a batch. To obtain comparative data, different strips from the same web crystal were diffused using P-8 and $POCl_3$. Thus, cell data is obtained on the same web crystal for both types of diffusion; and the results are immediately comparable.

The sheet resistivity of the N^+ surface was measured after phosphorus diffusion on both the $POCl_3$ and P-8 samples. The $POCl_3$ diffused cells had an average sheet resistivity of 55 Ω/□ which is within the specification and corresponds to a 0.2-0.3 μm junction depth. The P-8 diffused samples, however, averaged 28 Ω/□ which indicates a junction depth of about 0.5 μm, several tenths of a micron deeper than the $POCl_3$ diffused samples. This is at variance with previous scoping studies which indicated 890°C as the preferred diffusion temperature to obtain the desired sheet resistivity.*

The effect of the deeper junction is immediately obvious when the short circuit current density of the cells is examined. The $POCl_3$ diffused cells had an average J_{sc} of 27.4 mA/cm^2 while the P-8 diffused cells had an average J_{sc} of 26.7 mA/cm^2. This 3% difference in J_{sc} was reflected in the efficiency of the P-8 diffused cells which was also 3% lower than the $POCl_3$ diffused cells.

The 3% decrease noted in J_{sc} in this experiment can be compared to the expected decrease in cell current due to the different junction depths. At 0.5 μm junction depth, all wavelengths shorter than 430 nm would be absorbed in the heavily doped N^+ layer; and nearly all the carriers produced would recombine before collection. For a 0.25 μm junction, all wavelengths shorter than 405 nm would be absorbed in the dead layer. This 25 band width contains approximately 4% of the total photons in the solar AM-1 spectrum, and this number of photons will be absorbed in the N^+ region rather than in the bulk of the cell; therefore, there will be fewer photogenerated carriers in the bulk to be collected as a photocurrent. This 4% decrease is in rough agreement with the noted decrease in J_{sc}.

Further runs of this type are being evaluated.

C. Analysis of High Efficiency Runs

Eleven processing runs, tested and reported in the last several months and having high average efficiencies, were analyzed to determine the effectiveness of the liquid boron diffused back surface field.

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*Tests are underway to determine if the low ρ_s is due to the thick P-8 solution.

Table 5 gives the compiled data on eleven runs processed between December 15, 1982, and January 15, 1983. These runs were chosen as being representative of runs having high average efficiencies. In addition to the efficiency data, the average open circuit voltage and number of cells in the run are given. The open circuit voltage is a good measure of the quality of the back surface field due to the P^+P junction.

The presence of a high-low junction (i.e., P^+P) at the back surface of an N^+P cell structure will increase the short circuit current but mainly enhances the open circuit voltage. One important factor in limiting the efficiency of a solar cell is a high minority carrier recombination velocity at the cell surfaces. The back surface field reduces the back surface recombination velocity due to a potential energy barrier between the two regions (P^+P) which effectively causes a built-in field. This field reduces the loss of photogenerated carriers, enhancing the quantum efficiency of the base region of the cell and thereby increasing the open circuit voltage.

In Table 5, the average V_{oc} for all cells is 0.562V. The maximum V_{oc} measured was 0.598V. Hovel* gives calculated values of V_{oc} for N^+P cells fabricated on 1 Ω-cm and 10 Ω-cm silicon of 0.600V and 0.545V respectively. The cells reported here are fabricated on 4-8 Ωcm material, and the calculated V_{oc} should be 0.555. Thus, the 0.562V average reported and the 0.598V maximum indicate an effective back surface field.

The last column in Table 1 is the correlation coefficient between the V_{oc} and efficiency of the cells in the given runs. This coefficient in all cases is above 0.6 where 1.0 is perfect correlation and 0 is no correlation.

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*H. J. Hovel, "Semiconductors and Semimetals," Vol. II - Solar Cells Academic Press, New York, 1955.

TABLE 5

HIGH EFFICIENCY LIQUID BORON/LIQUID DIFFUSION MASK PROCESSING RUN

Run ID	Cell Area (cm^2)	No. of Cells	Av. V_{oc}(V)	Av. Eff. (%)	Correlation Coeff. r
1108-49M	15.68	46	.556	14.8	.77
1118-1M	15.68	48	.559	14.4	.70
1127-1M	15.68	48	.560	14.7	.74
1209-49M	15.68	45	.569	14.2	.64
1126-25M	15.68	53	.563	13.9	.89
1126-49M	15.68	32	.570	15.0	.75
1201-25W	19.60	53	.558	14.1	.73
1201-73W	19.60	37	.560	14.4	.92
1210-73W	19.60	43	.576	14.3	.79
1201-1W	19.60	47	.557	14.3	.96
2234-49E	24.80	21	.557	13.5	.93

Totals: No. of Cells - 473
Av. Eff. - 14.3%
Av. V_{oc} - 0.562V

The dark IV data on selected cells was measured at the Westinghouse R&D Center. The dark IV curve for solar cells can be expressed as follows:

$$J(V) = J_{01}\, e^{V/V_T} + J_{02}\, e^{V/nV_T}$$

where $V_T = \frac{kT}{q}$

k = Boltzmann constant

q = electronic charge

T = absolute temperature

n = diode ideality factor

J_{01} is the current density due to carrier diffusion through the bulk of the cell while J_{02} is current density due to recombination in the junction depletion region*. The cells tested showed low J_{01} and J_{02} values. The series and shunt resistance were below 0.5 Ωcm^2 and above 10K Ωcm^2 respectively. These data indicate that there were good cells with excellent junction characteristics.

In summary, the data presented here show an operating back surface field which enhances the V_{oc} and where the cell efficiency is controlled to a great extent by the open circuit voltage.

D. Evaluation of Low Efficiency Cells

During the period the liquid dopant process sequence has been investigated, a number of cells have been fabricated with very low efficiencies (in the 1% - 10% range). During this reporting period, 150 of these reject cells were analyzed to determine the cause of the low efficiencies.

Based on the measured lighted IV parameters, the 150 reject cells can be divided into 3 groups:

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*See TME 3158 on this contract submitted September 15, 1982.

Group 1 (about 15% of the reject cells)

This group contained cells having the following lighted IV properties:

V_{oc} > 0.5V

J_{sc} - variable

FF - variable

Efficiency - variable but less than 10%

These cells were mechanical failures for reasons such as: very thin or no copper plating, non-adherent grid fingers, broken or cracked cells, grid lines not completely opened, and a light copper flash over the entire surface. Thus, these cells could have been rejected prior to testing as mechanical failures.

Group 2 (about 5% of the reject cells)

These cells had no cosmetic defects with lighted IV properties as follows:

V_{oc} > 0.5V

J_{sc} > 20 mA/cm^2

FF < 0.6

Efficiency - 6-10%

Dark IV properties of representative cells from this group showed mediocre bulk lifetimes (50-110 μsec) and adequate junctions ($J_{02} < 10^{-6}$A) but with high series resistance or low shunt resistances. These spurious resistances cause the low fill factor and low efficiency. These resistance problems are related to processing problems.

Group 3 (about 80% of the reject cells)

These cells also showed no cosmetic defects. The lighted IV properties are listed below:

V_{oc} < 0.4V

J_{sc} < 20 mA/cm^2

FF < 0.6

Efficiency - 1-6%

Dark IV measurements showed normal series resistance with a low shunt resistance. The bulk lifetime was less than 1 microsecond, and the junction current density exceeded 10^{-4} A/cm^2.

Eight cells were selected from this group, and the contact metals and antireflective coatings were removed. The sheet resistivity and conductivity type were then measured on these bare cells. This data, shown in Table 6, indicates the back (P^+) surface is not at fault. The sheet resistivity is within specification, and the conductivity is strongly P-type. Analysis of the front surface, however, indicated considerable problems. The sheet resistivities are quite variable, and the conductivity varies from N to P over the surface.

These results indicate that during the initial boron diffusion, the sun side of the cell (protected by the liquid SiO_2 mask) became contaminated with boron which shorted out the (later diffused) N^+P junction. These shorted regions would account for the low shunt resistance and very low bulk lifetime.

This front surface contamination may have occurred during the liquid boron application where the liquid "wicked" by capillary action to the sun side and was subsequently driven in. A second more probable cause of contamination is that the protective liquid SiO_2 mask contains small pinholes through which boron (in the furnace tube ambient) diffuses.

In either case, the integrity of the liquid mask must be questioned. In fact, several runs made in late 1982 used a liquid SiO_2 mask with BBr_3 diffusant gas. These runs had a significantly large number of rejects. This result is consistent with the theory of pinholes in the SiO_2 mask.

From this analysis, it is concluded that the liquid SiO_2 mask will, on occasion, permit boron to diffuse through and thus degrade the sun side surface of the cell.

Since the liquid mask is applied using a sponge-squeegee, it is quite possible that non-uniform thickness and coating techniques can lead to pinholes. The

TABLE 6

ANALYSIS OF REJECT CELLS

Cell No.	Avg. Sheet Resistivity (Ω/□) Front	Avg. Sheet Resistivity (Ω/□) Back	Conductivity Type Front	Conductivity Type Back
4A	55	45	Spotty N & P	Strong P
77C	100	44	Spotty N & P	Strong P
59A	95	40	Spotty N & P	Strong P
79C	90	35	N	Strong P
88A	30-100	35	Heavy P in spots	Strong P
66B	65	40	P	Strong P
44C	65	40	Spotty N & P	Strong P
53A	80	40	Spotty N & P	Strong P

problem may be obviated when the layer can be applied using the meniscus coater which has been shown to give uniform layers.

It should also be noted that in the vast majority of cases (over 88 percent of the time), the SiO_2 mask performs quite well. The solution to the reject problem discussed previously is to improve the method of application.

E. Meniscus Coating Application Studies

The meniscus coater was damaged in shipment to Westinghouse and returned to Integrated Technologies for examination and repair. The damage to the equipment was quite extensive, and the repair was not complete until February, 1983. Cost of repair to the equipment, which is Westinghouse owned, was borne by Westinghouse.

The rebuilt meniscus coater was source inspected at the vendor's plant in February. The acceptance tests were carried out using an antireflective solution. This solution was selected because it allows the most rapid assessment of coating thickness and uniformity. In the test, fifteen web strips, each 33 cm, were coated with a standard AR coating solution. The strips were numbered 25, 44, and 47. The coating speed was 21-24 inches/min. After coating, the strips were baked at 400°C for 15 minutes in air. The general appearance of all strips was good, and three strips (numbered 25, 44, and 47, respectively) were selected for further study.

General Appearance of Strips:

- #25 - only 28 cm coated due to break on end of strip. This strip was etched in KOH at Integrated Technologies before coating. Color was light blue and was acceptably uniform over the surface.
- #44 - Coated entire length, deep purple-blue, slight variation in color over surface noted.
- #47 - Coated entire length, deep purple-blue except at one end where there was a gold colored stripe. This was caused by the web not being held firmly in the vacuum chuck.

On all samples, there was no significant carryover of the AR coating on the uncoated side.

The three strips were sent to Westinghouse R&D Center where the thickness was measured at 20 uniformly spaced positions along the length of the web using an ellipsometer. The measurements were taken within ±1 cm of the centerline of the web. The data is shown in Table 7.

These three strips along with the 12 others were part of a cell processing run. After the thickness measurements were made, all strips were merged with the original run and the processing completed. Table 8 gives data on this run.

The data in Tables 7 and 8 indicate that the "CAVEX" meniscus coater is suitable for applying an antireflective coating. Since the thickness control of the AR coating is the most critical and the meniscus coater can achieve this control, the coater will certainly be suitable for the other applications planned, e.g., liquid SiO_2 deposition and liquid dopant deposition, specifically liquid phosphorus.

After completion of the source inspection tests, the meniscus coater was crated and shipped to Westinghouse. The unit arrived undamaged in the last week of February.

Figure 1 is a photograph of the meniscus coater after its receipt at AESD. The unit has been placed in the diffusion area of the Westinghouse pre-pilot facility. In the photograph, the web holding fixture portion of the machine, which will simultaneously support up to ten strips of web during liquid application operations, is shown in the upright (half-open) position. Final assembly and checkout of this equipment will be completed in early March. The unit will then be used to complete the liquid phosphorus diffusion tasks specified in the contract.

F. Evaluation of Silicon Shot Material

Eight web growth furnace runs were made in December to evaluate the silicon shot produced in the shot tower installed at AESD. In general, several crystals were grown from the melts before the shot was introduced. Crystals were grown during the remainder of the run using AESD silicon shot as the replenishment material.

TABLE 7

MENISCUS COATER ACCEPTANCE TEST DATA: THICKNESS OF AR COATED STRIPS

Strip #	Coating Thickness Along Length (Å)	Strip #	Coating Thickness Along Length (Å)	Strip #	Coating Thickness Along Length (Å)
25	847	44	712	47	716
	857				703
	848		[illegible]		724
	834		698		742
	838		713		739
	832		701		695
	835		683		602*
	827		679		648*
	833		711		721
	845		700		718
	809		683		724
	799		709		718
	798		703		730
	815		707		700
	840		691		687
	815		687		726
	819		699		718
	819		690		711
	818		690		724
			720		689
	Av = 828 ±17		Av = 700 ±12		Av = 707 ±33

On Strip #47, the two thickness values (marked with an asterisk) correspond to the noted gold colored stripe. If these two values are neglected, the average for #47 is 716 ±16.

It is estimated that an AR coating thickness variation of ±20A is suitable for the process sequence.

TABLE 8

DATA FROM CELLS PROCESSED WITH AR COATING APPLIED BY MENISCUS COATER

A. Cell Run No: 1313-1

B. Efficiency Data Comparison

AR Application Technique	No. of Cells	Avg. Efficiency
Dip/Withdrawal	12	12.0%
Meniscus Coater	35	12.2%

C. AR Enhancement Factor* of Meniscus Coated Cells

$$\frac{V_{oc}\ (\text{coated})}{V_{oc}\ (\text{uncoated})} = 1.01 \pm 0$$

$$\frac{I_{sc}\ (\text{coated})}{I_{sc}\ (\text{uncoated})} = 1.44 \pm 0.02$$

$$\frac{FF\ (\text{coated})}{FF\ (\text{uncoated})} = 1.01 \pm 0.03$$

$$\frac{\text{Efficiency (coated)}}{\text{Efficiency (uncoated)}} = 1.46 \pm 0.03$$

*The enhancement factor was determined by measuring the IV properties of the cell, removing the AR in a dilute HF solution, and remeasuring the cell. Six cells were tested in this way.

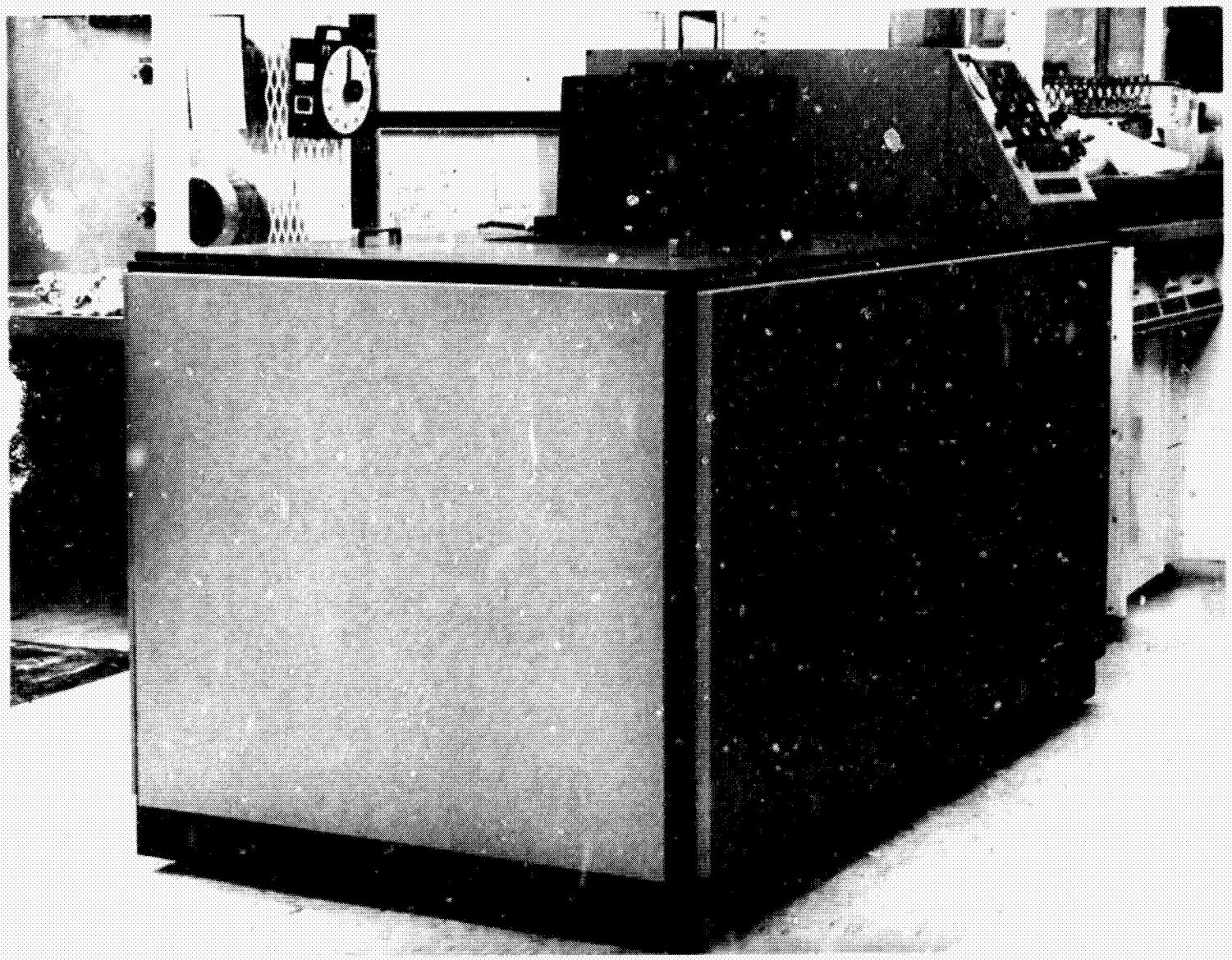

Figure 1. Meniscus Coater, Recently Delivered to the Westinghouse Pre-Pilot Facility

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TABLE 9

AVERAGE EFFICIENCIES OF CELLS GROWN IN RUNS USING AESD SILICON SHOT AS REPLENISHMENT MATERIAL

Condition	Cell Size (cm x cm)	No. of Cells	Average Efficiency, %
Initial Melt	1.6 x 9.8	25	13.8 ±1.7
After Replenishment	1.6 x 9.8	73	13.2 ±2.2
Initial Melt	2.0 x 9.8	34	12.9 ±1.9
After Replenishment	2.0 x 9.8	62	12.7 ±2.0

With this procedure, the first web crystals grown were composed of the standard semiconductor grade silicon. The later web crystals, due to replenishment, contained increasingly more silicon melted from shot material.

These web strips are being processed into cells using the Westinghouse baseline process sequence, and initial data from these cells have been analyzed during the past reporting period. Both 1.6 x 9.8 cm and 2.0 x 9.8 cm cells were produced in these runs.

The average efficiencies of cells made from web grown from the initial melt and after the introduction of shot into the melt as replenishment material are given in Table 9. The small differences in these averages are believed due to the inclusion of this web in many processing batches (some of which were part of ongoing experiments). A normalized distribution of cell efficiencies is shown in Figure 2. Considering the small number of cells in this sample, this distribution is not significantly different than that obtained in normal processing (including experimental batches). Although a larger data base is required, it is tentatively concluded that the material made in the shot tower installed at AESD does not degrade cell properties; and the shot produced qualify as silicon melt replenishment material for solar cell production.

G. Delivery of Material for Ion Implantation Studies

During this period, 138 pieces of web, each 2.1 cm x 5.0 cm, were delivered to JPL for ion implantation studies by Spire Corporation. These pieces were laser scribed from dendritic web strips to the proper size, and the bulk resistivity of each piece was measured. These resistivity data were transmitted along with the samples.

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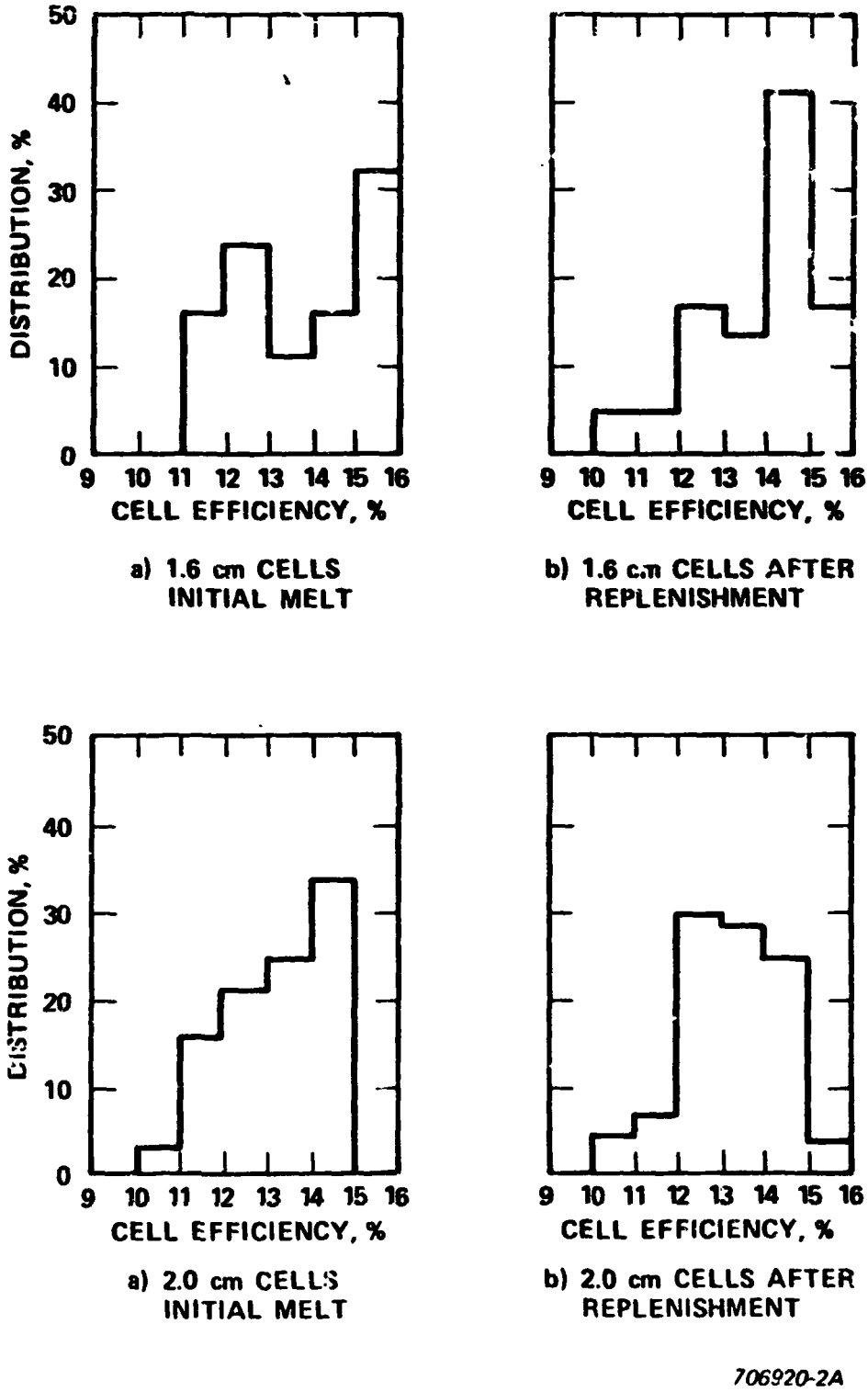

Figure 2. Normalized Efficiency Distribution of Cells Produced from Web Grown from Runs using AESD Silicon Shot Replenishment

IV. ACTIVITIES PLANNED FOR NEXT QUARTER

A. Continue to analyze cell processing runs using the liquid boron baseline sequence.

B. Complete initial tests of liquid phosphorus deposition using the meniscus coater.

C. Optimize liquid phosphorus dopant drive parameters.

D. Initiate a cost analysis on the all liquid baseline process sequence.

V. PROGRAM DOCUMENTATION

All programmatic documentation specified in the Westinghouse Process Research of Non-CZ Silicon Material MEPSDU contract has been submitted in accordance with schedular requirements. A list of the programmatic documentation and submittal dates is compiled in Table 10.

TABLE 10

PROGRAM DOCUMENTATION SUBMITTAL STATUS

Item	Submittal Date
1. Monthly Technical Reports	
A. March 1982	April 1, 1982
B. April 1982	May 3, 1982
C. May 1982	June 3, 1982
D. June 1982	July 8, 1982
E. July 1982	August 2, 1982
F. August 1982	September 7, 1982
G. September 1982	October 7, 1982
H. October 1982	November 8, 1982
I. November 1982	December 6, 1982
J. December 1982	January 10, 1983
K. January 1983	February 6, 1983
L. February 1983	March 7, 1983
2. Financial Management Reports	
A. March 1982	April 6, 1982
B. April 1982	May 19, 1982
C. May 1982	June 14, 1982
D. June 1982	July 16, 1982
E. July 1982	August 16, 1982
F. August 1982	September 14, 1982
G. September 1982	October 15, 1982
H. October 1982	November 15, 1982
I. November 1982	December 15, 1982
J. December 1982	January 14, 1983
K. January 1983	February 16, 1983
L. February 1983	
3. Program Plan, Cost Estimates, & WBS	
A. Original	March 12, 1982
B. Revision	May 26, 1982
4. MEPSDU Summary Report	
A. Draft	June 3, 1982
B. Final	July 26, 1982