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A MODULE EXPERIMENTAL PROCESS SYSTEM DEVELOPMENT UNIT (MEPSDU)

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Quarterly Report No. 4

September 1, 1981 - November 30, 1981

Contract No. 955902

SOLAREX CORPORATION

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

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ABSTRACT

The purpose of this program is to demonstrate the technical readiness of a cost-effective process sequence that has the potential for the production of flat plate photovoltaic modules which meet the price goal in 1986 of 70¢ or less per Watt peak.

The major accomplishments of the program to date have been the development of an improved AR coating technique, the development of sand blast back clean-up to reduce clean up costs and to allow much of the Al paste to serve as a back conductor, and finally the development of wave soldering for use with solar cells.

During the quarter, program efforts included:

- Suspension of all module processing efforts per JPL's orders.

- Redefining the program budget, schedule and program plan to reflect the reduced funding level and scope of work.

- Processing of control and test material via a controlled process sequence to determine the material capabilitiy.

- Experimentation with diffusion barrier materials.

- Cell processing to evaluate different process steps.

- Preparation of a Cell and Minimodule Test Plan.

- Collecting data for preliminary Samics cost analysis.

QUARTERLY REPORT

TABLE OF CONTENTS

1.0 INTRODUCTION

The purpose of the MEPSDU program was to demonstrate the technical readiness of a cost-effective process sequence that has the potential to produce flat-plate photovoltaic modules which meet the 1986 price goal of less than $.70 per peak Watt. To achieve this goal, Solarex was to design, develop and fabricate a Module Experimental Process System Development Unit (MEPSDU) and to utilize the unit to produce a quantity of modules using the proposed process sequence. The scope of this program has now been changed to eliminate module building and to concentrate on verification of the process steps and adaptibility to the use of automated equipment. This effort will include:

- Design and development of a detailed cost effective cell process sequence.
- Identification of automated equipment capable of performing this process sequence.
- Verification of the process sequence and determination of the expected performances.
- Preparation of a process instruction manual, including in-line process control information.

- Performance of a minimum of three technical demonstrations which will include the production of sufficient cells and collection of production data to permit validation of the contract goal.

- Performance of a cost analysis of the process sequence, including a study of the cost impact and changes required in the MEPSDU to allow the use of different types of input material.

The emphasis of the program has been shifted from demonstration of an automated production line to the development of a high efficiency low cost cell process sequence compatible with automated processing. Solarex has committed to the purchase of the necessary equipment to demonstrate each process step in an automated mode.

To date the program has been successful in developing three new processes that can reduce cell cost and improve efficiency. The three are:

1. AR Coating - A new technique involving the spraying of pure titanium isopropoxide onto heated wafers resulted in a significant improvement in AR coating uniformity especially for less smooth surfaces. This technique should be less expensive than

previous spray methods because the use of solvents has been eliminated.

2. Glass Bead Back Celan-Up - The use of glass bead back clean-up not only eliminated the need for costly chemicals, but also allows the Al to serve as the prime current carrier on the back of the cell, saving the cost of having to apply additional metal (such as solder) to provide for current collection.

3. Wave-Soldering - Using wave-soldering to apply the front pattern solder allows more control of the process, reduces the amount of solder utilizes and makes the solder step more adaptable to automation.

Further improvements in these processes, identification of other improved low cost process steps, and the coordination of these processes into a process sequence are the program efforts now underway.

The present baseline process sequence is described in Section 2.1. Optional areas still being investigated are described in Section 2.2. Technical Progress for the fourth quarter is presented in Section 3 along with the initial SAMIC results for a MEPSDU pilot facility. Section 4 discusses the major technical questions remaining and presents a brief description of the program efforts scheduled for the fifth quarter.

2.0 PROCESS DESCRIPTION

2.1 Baseline Process Sequence

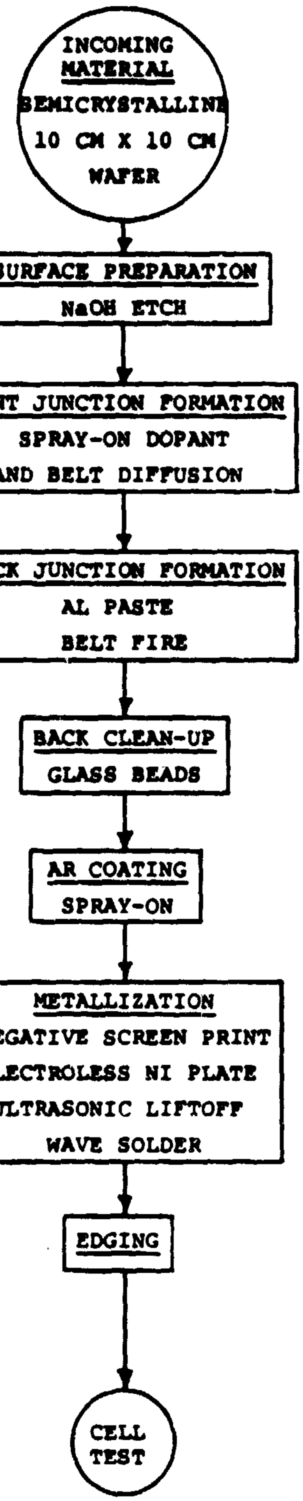
The baseline process sequence is shown in block form in Figure 1. This process sequence was described in detail in the First Quarterly Report (1) and the modifications described in the Second and Third Quarterly Reports (2,3). The baseline process sequence includes the following features:

- Semicrystalline silicon (10cm x 10cm) as the silicon input material;
- Spray-on dopant diffusion source;
- Belt diffusion;
- Al paste BSF formation;
- Glass bead back clean-up;
- Spray-on AR coating;
- Electroless Ni plate-solder metallization; and
- Edging.

FIGURE 1

GENERAL PROCESS

DESCRIPTION



2.2 Options in Process Sequence

Most of the process steps have been determined and preliminary performance verification completed. However the edging step has not been finalized. Initially laser scribing was selected, but problems with the compatibility of laser scribing and electroless Ni plating lead to the search for an alternate edging technique

At present the following techniques are under consideration:

- Ion milling;
- Masking the edges with a diffusion/Ni plating barrier;
- Sand blasting;
- Grinding; and
- Laser with an edge follower that chamfers the edge.

Experiments in some of these areas are discussed in Section 3.0.

3.0 TECHNICAL PROGRESS

3.1 Documentation

The following technical documents were submitted during this quarter:

17. Quarterly Report No. 3.
18. Technical Progress Report No. 10.
19. Technical Progress Report No. 11.
20. Technical Progress Report No. 12.
21. Proposal for Continuation of Contract.

3.2 Pilot Line Processing

The first three pilot runs were reported in the Quarterly Report #3 (3). Table 1 summarizes the first four pilot runs that were completed before redirection of the program meant that no preprototype modules were required. In the fourth pilot run the yield was lower than expected due to technical difficulties. In this particular pilot run, the spray-on titanium isopropoxide ARC appeared impervious to 70% Fumic HF. Since metallization depends upon clearing the printed pattern of all oxides, this is a critical step.

TABLE 1

MEPSDU PILOT RUNS

		# STARTS	YIELD(90%)	EFF.	CURRENT DENSITY AM1	RED	BLUE	VOC	CELLS 8% OR GREATER
1	SEMI	250	27%	7.2%	23.30	13.52	6.10	541	41
	SINGLE	25	64%	7.6%	22.97	14.29	5.31	528	
2	SEMI	246	37.8%	7.5%	23.56	13.73	6.12	542	72
	SINGLE	25	80%	8.9%	25.7	16.35	5.73	554	
3	SEMI	250	10.8/15.6%	7.6%	25.30	16.00	6.68	530	30 Lost 175 Cells Due to Heavy Oxide
	SINGLE	25	24%	9.45%	26.7			562	
4	SEMI	200	32.5%	7.2%	24.0			552	42 NOTE: 25 Wafers Extracted for Another Experiment
	SINGLE	25	68%	9.35%	27.3			591	

Experimentally it was observed that the central region of the cells was the most difficult area to clear, which corresponded to a "hot" spot in the center of the hotplate used in the application of the AR spray. This is evidence that there is a time-temperature function of the AR oxidation process which was previously unknown. Efforts to better characterize the AR coating technique are underway.

A second problem which has previously been observed is the non-continuity of solder across fingers of the cell pattern. This effect appeared to correspond to small brown or black spots on the plated nickel layer. In the fourth pilot run, these spots were removed from the nickel by dipping the cells in 1 M HCl for several seconds, (and rinsing and drying) prior to solder dipping. This treatment improved the contact continuity on most wafers to some extent, but did not completely remove the problem.

Pilot Run 4 suffered from low yield due to shunting problems. There were not edge problems, but were related to the bulk silicon and appeared to be due to inadequate removal of saw damage.

3.3 Control and Test Material Evaluation

A procedure was initiated to verify the suitability of silicon for the MEPSDU experimental work. This procedure involves the fabrication of solar cells by a "standard" process - JPL Contract 955307 - Analysis of the Effects of Impurities in Silicon (4). The performance of the test silicon can then be measured against the data compiled in the earlier program (5,6 & 7).

Three categories of silicon were selected for the first verification run, Lot 23:

1. 4" round <100> Monsanto single crystal.
2. 5" round <100> Rockwell International single crystal.
3. 5 wafers sampled from "Grade A" semicrystal.

A summary of the results appears in Table 2. These categories of silicon will be used in later MEPSDU experiments. The results show consistent high efficiency from the 4" single crystal, consistent but lower efficiency for the 5" single crystal and consistent moderate efficiency from the semicrystalline silicon.

TABLE 2 - LOT 23

AM1 - 25^{O}C MEASUREMENTS

(2cmx2cm - SPACE PROCESS)

GROUP	NO.	$\overline{P}$(mW)	EFF (AM1)	$\overline{I}$sc	$\overline{V}$ol	$\overline{F}$F
4" S.C.	23	62.6	15.64%	135.1	592.4	.782
5" S.C.	19	58.8	14.69%	131.5	593.3	.752
Semi	57	50.4	12.59%	119.2	562.8	.750

3.4 Diffusion Barriers

A number of experiments have been conducted in an attempt to find a material suitable for use as an easily applied diffusion and etchant barrier. Initially we looked at screenable glasses from Englehard including A3025, A3031, A2835 and 4287C. All of these materials easily etched away in fumic HF after firing. They also tended to be very brittle and easily chip off during normal handling.

We then identified a number of metal oxides in which oxide formation takes place at temperatures below the diffusion temperature used, but whose melting temperature is well in excess of silicon's melting point. Eight candidate materials were selected. These were stanous oxide, titanium isopropoxide, titanium cloride, magnesium acetate, magnesium carbonate, niobium cloride, chromium trioxide and tungsten cloride. A paste was made with each of these powders, using the same formula as we use for aluminum paste. This may not be the best formulation, but at least provided a vehicle for testing. After firing these pastes at 500°C, they were all succeptible to HF etch. However after being put through a diffusion time-temperature cycle titanium isopropoxide, titanium cloride, niobium cloride and chromium trioxide withstood the fumic HF treatment. These four materials are now being tested for their ability to act as a barrier to the phosphorous diffusion.

3.5 Wave Soldering

After initially setting up the machine, it was heated to 225°C. The initial angle of the transport rails to the solder pot was 8°, as recommended by the Hollis people. The speed of the transport chain was 50 in. per min. The first cells soldered well, but there was some balling along the grid lines. This was helped by increasing the angle to 9°. The speed of the chain was slowed down to about 40 in/min. This helped increase the amount of solder left on the pads. One additional observation was that in warm water the anti-dross oil was removed in 1/4 to 1/3 less time and more completely than in cold tap water.

Two groups of fifty cells were fabricated, with half being wave soldered and the other half solder dipped. The results are shown in Table #3.

TABLE #3

WAVE SOLDER VERSUS SOLDER DIPPING

EFFICIENCY DISTRIBUTION

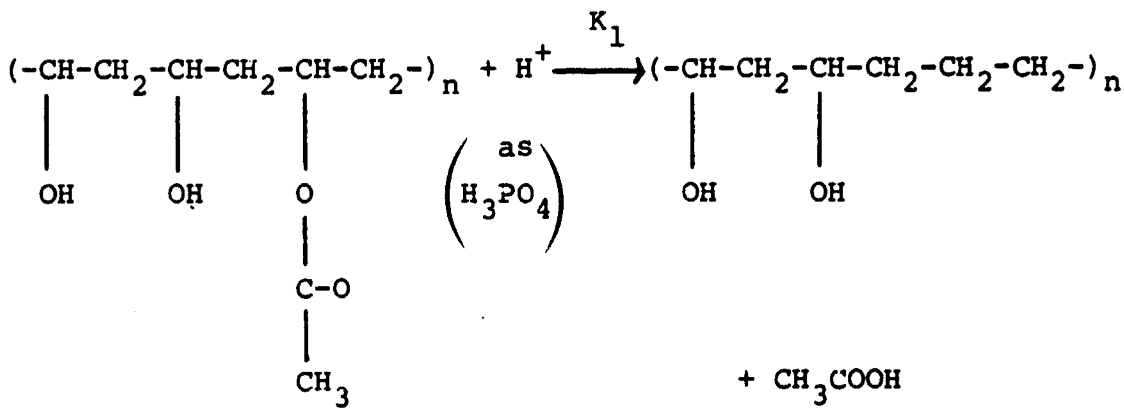
EFFICIENCY (%)	WAVE SOLDER (# OF CELLS)	SOLDER DIPPING (# OF CELLS)
Above 9	0	12
8 - 9	26	19
6 - 8	8	11

The wave soldering produced less scatter in the results although the average efficiencies were similar. It is clear that more work is required to optimize the wave solder process, but the consistency of results in the initial experiments is encouraging.

3.6 Spray Doping

Several experiments using both single crystal and semicrystalline silicon failed because the Emulsitone Phosphorofilm failed to wet the silicon. A fresh batch of dopant was received and did wet the silicon.

Analysis of both old and new lots of dopant indicate that the polymer (poly) vinyl alcohol is undergoing decomposition in the acidic solution. The (poly) vinyl alcohol is produced by hydrolysis of (poly) vinyl acetate. Hydrolysis is typically incomplete, leaving acetate groups in place on the carbon chain, which then react with acid (H+) to generate acetic acid:



Titration curves on old and new samples show the presence of acetic acid and phosphoric acid in old samples, but only phosphoric acid in new samples. The rate constant of the above reaction is unknown (k_1) but the dopant appears to deteriorate beyond use within 2 - 3 months when stored at room temperature.

3.7 SAMICS Cost Analysis

Continued effort is underway to develop a cost basis for a 6.6 MW output MEPSDU pilot line. The calculations are based on 10% efficient cells with 80% yield in a three shift 345 days per year operation. The operation is designed to provide 1,000 good cells output per hour of operation. Table #5 lists the required materials, the amounts needed per wafer, the cost of the item taken from the cost accounting catalogue, the calculated cost per wafer, the number of wafers processed in one year and the total cost per year of this item.

Table #6 summarizes the 6.6 MW facility. The various columns are defined below:

1. The process step.

2. Yields expressed as the percentage of cells starting in

TABLE #5

MATERIALS COST - MEPSDU

1,000 WAFERS PER HOUR

OPERATION	ITEM	AMT/WAFER	COST OF ITEM $	COST PER WAFER $	# OF WAFERS/YR IN 000,000	COST PER YEAR
ETCH	NaOH	0.01 Kg	.18*/Kg	.0018	8.25	14,850*
	HCl	0.0011 liter	1.13/ltr	.0012	8.25	10,255
	Deionized H_2O	0.06 gallons	0.135/gal	0.0021	8.25	17,424
DIFFUSE	Dopant	0.64 cm^3	$35/gal	0.006	8.15	48,900*
BSF FORMATION	Al Paste	0.65 cm^3	0.002/gm	.0035	8.05	28,175
	Screens	5.10^{-5}	55*screen	.00275	8.05	22,138*
	Squeegy Blades	$3.75.10^{-4}$	2.4*/blade	.00083	8.05	6,704*
BACK CLEAN-UP	Glass Beads	2.10^{-4} lb	$1/lb*	.0002	7.95	1,590*
	Fumic HF	1.0 ml	0.67/lb	.002	7.95	15,900
	Deionized H_2O	0.06 gal	0.035/gal	0.0021	7.95	16,695
AR	Titanium Isopropoxide	0.65 cm^3	$15/kg*	.0093	7.86	73,098*
PRINT INK & ETCH PATTERN	Colonial Ink	2 cm^3	49.65/gal*	0.026	7.76	203,310*
	Screens	$1.7.10^{-4}$	55/screen*	.0094	7.76	72,556*
	Squeegy Blades	$3.75.10^{-4}$	2.4/blade*	.00083	7.76	6,441*
	Fumic HF	1.0 ml	0.67/lb	.002	7.76	15,520
	Deionized H_2O	0.06 gal	0.035/gal	0.0021	7.76	16,296
NI PLATE & RESIST REMOVAL	Electroless Ni	0.005 gal	$5.00/gal*	0.025	7.67	191,750*
	Trichloro-ethylene	$4.5.10^{-4}$ gal	$21.73/gal*	0.0098	7.67	75,000*
ION MILLING	Filaments	$1.25.10^{-4}$	$5.00*	0.00062	7.5	4,650*
	Oil	$1.4.10^{-6}$ gal	100.00/gal*	$1.4.10^{-4}$	7.5	1,050*
	Argon	4.10^{-7} tank	$60/tank	$2.4.10^{-5}$	7.5	180*
WAVE SOLDER	Solder	0.1 cm^3	5.18/lb	0.0086	7.33	63,038
	Flux	0.5 cm^3	0.0020/cm^3	0.001	7.33	7,330
	Water	0.06 gal	0.0093/ft^3	$7.4.10^{-5}$	7.33	545

* Price not found in SAMICS Cost Account Catalogue or the price in the catalogue was not considered accurate.

TABLE #6

SUMMARY OF 6.6 MW FACILITY COSTS

(1) PROCESS	(2) YIELD BEYOND START OF STEP	(3) EQUIPMENT COST $,000	(4) WORKER PER SHIFT	(5) DIRECT LABOR COST PER YEAR $,000	(6) MATERIAL COST FOR 1 YEAR $,000	(7) EQUIPMENT LIFETIME (YEARS)
ETCH	80%	65	1	70.5	42.5	5
DIFFUSION	81%	173	1	70.5	48.9	10
BSF FORMATION	82%	83	½	32.9	57.0	10
BACK CLEAN-UP	83%	138	1	70.5	34.2	3
AR	84%	104	½	32.9	73.0	10
PRINT INK & ETCH PATTERN	85%	126	1	70.5	313.8	10
NI PLATE AND REMOVE RESIST	86%	50	1	70.5	266.8	5
ION MILL	88%	135	1	65.8	5.9	10
WAVE SOLDER	89%	100	1	65.8	70.1	5
CELL TEST	90%	55	2	150.4	0	10
TOTAL		1,029	10	700.3	912.2	

this step that pass final cell test.

3. Equipment cost in thousands of dollars for the pilot line.

4. The number of workers per shift required for each process step.

5. Direct labor cost per year in thousands of dollars required for the number of shifts described in 4) based on the salary scale from the SAMICS Short Course (8) and a 4.7 shift factor as used in the Short Course.

6. The total direct material costs per year in thousands of dollars (a sum of the materials listed in Table #5).

7. Estimated equipment lifetime in years.

The SAMICS analysis has not been completed since the utility and floor space requirements have not been calculated. The information in Table #6 can be used to find the dollar per watt cost of equipment, labor and materials using IPEG2. The IPEG2 equation is given below.

$$\text{COST} = \frac{\text{Ci} \times \text{EQPT}_i + 209 \times \text{SQFT} + 2.1\ \text{DLAB} + 1.2\ (\text{MATS} + \text{UTIL})}{\text{QUAN}}$$

The coefficients Ci are given in Table #7.

Using these coefficients the IPEG2 costs for equipment, labor and materials are given in Table #8. These are typically the major cost drivers and yield a total of $0.481. The values for square footage and utilities will be presented in the next quarterly report.

TABLE #7

EQUIPMENT COEFFICIENT

EQUIPMENT LIFETIME	3	5	7	10	15	20
COEFFICIENT	0.83	0.65	0.57	0.52	0.48	0.46

TABLE #8

DOLLAR PER WATT COST

PROCESS	EQUIPMENT	LABOR	MATERIALS
ETCH	0.0064	0.0224	0.0077
DIFFUSION	0.0136	0.0224	0.0089
BSF FORM.	0.0065	0.0105	0.0104
BACK CLEAN-UP	0.0174	0.0224	0.0062
AR	0.0082	0.0105	0.0133
PRINT INK	0.0099	0.0224	0.0571
NI PLATE	0.0049	0.0224	0.0485
ION MILL	0.0106	0.0209	0.0011
WAVE SOLDER	0.0098	0.0209	0.0127
CELL TEST	0.0043	0.0479	0
TOTAL	0.092	0.223	0.166

4.0 RECOMMENDATIONS AND SCHEDULE

The program emphasis is now on process development. The areas now being emphasized are:

- Characterizing and optimizing the spray AR technique.
- Development of an edging technique compatible with the remainder of the cell process sequence, with the semi-crystalline silicon, with automated production and with the program cost goals.
- Metallization process development so that cells with finer grid lines and higher efficiency can repeatedly be fabricated.

In addition to these development areas program efforts in the areas of cell test and SAMIC Cost Analysis are continuing.

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3. Solarex Corporation, A Module Experimental Process System Development Unit (MEPSDU), Third Quarterly Report, August, 1981, JPL Contract No. 955902

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