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DEVELOPMENT OF METHODS AND PROCEDURES
FOR HIGH RATE LOW ENERGY EXPENDITURE
FABRICATION OF SOLAR CELLS

Quarterly Progress Report No. 2, January 1—March 31, 1976

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Work Performed Under Contract No. JPL 954289

Simulation Physics, Incorporated
Burlington, Massachusetts

ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
Division of Solar Energy

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SIMULATION PHYSICS

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ABSTRACT

This program involves ion implantation and processing by pulsed electron beams to fabricate silicon solar cells in vacuum at high speed without the use of high temperature operations. Individual elements of the method are being successfully developed and program objectives are being approached.

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1.0 INTRODUCTION

Simulation Physics is developing an approach to fabrication of silicon solar cells which promises to be fast, inexpensive and efficient in its utilization of materials and energy. The development is based upon the use of ion implantation in conjunction with pulsed energy methods replacing conventional thermal operations to allow fabrication of cells entirely under vacuum with the cell wafer maintained at room temperature throughout processing. The program objective is to accomplish fabrication of approximately 11% efficient (AMO) 2 x 2 cm cells with actual process duration less than 120 seconds and cell surface energy deposition less than 5 calories/cm².

Status of the program as of January 1976 was given in Quarterly Report No. 1. At that time ion implanted solar cells had been demonstrated using only vacuum operations performed at room temperature. Best cell performance achieved was approximately 9% AMO with cell currents and curve factors equivalent to those observed with conventionally processed ion implanted cells but with open circuit voltages slightly lower.

During the past three months effort has involved development of individual procedures which are to be combined for achievement of program objectives. Implantation conditions for phosphorus and boron to produce an N⁺/PP⁺ structure are being

investigated. Cell metallization development has emphasized aluminum in order to minimize cost and process complexity. Pulsed electron beam capability has been extended to allow processing of larger areas. Cell fabrication sequences have been shortened such that total process time objectives are now being approached.

2.0 TECHNICAL DISCUSSION

2.1 Ion Implantation

Equipment used for ion implantation is inherently expensive and complex. It is probable that in a full scale solar cell production facility based upon the processing concepts being developed under this program, the implanters used for introduction of the junction and back contact underlayers will determine throughput limitations.

The ion implanter at Simulation Physics delivers scanned beams of 200 μA of phosphorus or 50 μA of boron at energies between 25 and 200 keV. Lower beam currents are produced at energies down to 5 keV. High current machines are available which deliver up to 3 mA of phosphorus and 1 mA of boron. Next generation machines of up to 100 mA are now under conceptual design.

Experimental work on junction introduction has involved examination of implant energies from 5 through 200 keV and fluences from 5×10^{13} to 10^{16} ions/cm². Best cell performance characteristics are achieved at lowest energy and modest fluence. However such cells are for several reasons not compatible with the processing constraints of this particular program. Phosphorus implant parameters expected to be utilized for process demonstrations of this program remain as 1×10^{15} ions/cm² at 25 keV. In 10 ohm-cm material resulting junction depth and sheet

resistance are approximately $0.3 \mu\text{m}$ and $100 \text{ ohms}/\square$ respectively. Cell area throughput capabilities of $200 \mu\text{A}$, 3 mA and 100 mA implanters under $10^{15} \text{ ions}/\text{cm}^2$ fluence requirements are 1.2, 18 and 600 cm^2 per second respectively.

The all vacuum processing being developed assumes a clean, properly surfaced silicon wafer to start but does not provide for cleaning, etching or other alteration of the wafer surfaces during fabrication. Application of an adequate ohmic back contact to the lightly doped cell base region is difficult in these circumstances and it is expected that it will be necessary to utilize a P^+ underlayer at the interface. Usually alloyed aluminum is excellent for this purpose but in the present case, in order to minimize processing time, the necessary heavy surface doping will be produced by boron ion implantation.

Investigation is in progress to identify minimum conditions for satisfactory P^+ layers by boron implant. Figure 1 compares AMO I-V characteristics of otherwise identically processed cells with P^+ layers introduced by alloying an evaporated aluminum layer at 650°C for 15 minutes and by implanting 10^{15} boron ions per cm^2 at 25 keV. In the experiment implants were furnace annealed at 750°C for one hour and titanium silver contents were sintered at 605°C for 5 minutes. Although they show somewhat low curve factors due to low fluence junction implants, both cells of Figure 1 exhibit satisfactory back contact behavior.

2.2 Contacts

It is planned that front and back contacts of cells to be fabricated will be of aluminum deposited by vacuum evaporation then pulse sintered. In conjunction with the back surface P^+ underlayer investigation, a test was conducted to determine the electrical quality of contacts deposited directly onto a polished surface of a lightly doped silicon wafer. Aluminum was alloyed into the back surface of a number of $10\ \Omega\text{-cm}$ P-type silicon wafers without junctions. The back surfaces were then metallized to produce low resistance ohmic contacts. Onto the polished front surfaces of these wafers were evaporated arrays of 0.3 cm square metallization patches. For purposes of comparison, both titanium-silver and aluminum were used with depositions performed onto substrates at room temperature and at 250°C . Dark current-voltage characteristics were then measured between front and back metallization on each sample type as deposited and after furnace sintering or pulsed sintering in an electron beam.

Two types of behavior of the contacts to the polished silicon were observed and are illustrated in the examples of Figures 2 and 3. Aluminum contacts, except those deposited at room temperature and not subsequently sintered, were ohmic at approximately 3 ohms corresponding to the silicon wafer resistance in the configuration used. As in the example of Figure 3,

Figure 2.

Example of Ohmic Contact
I-V Characteristic.

Figure 3.

Example of Nonohmic Contact I-V Characteristic.

the room temperature unsintered aluminum contacts and all of the titanium-silver samples showed blocking behavior in one direction and a forward pattern characterized by an approximately 3 ohm resistance after reaching a turn-on or barrier voltage. Results are summarized in Table 1.

The aluminum contacts, either furnace or pulse sintered, exhibited good performance even in the absence of a P^+ underlayer. The results suggest that for aluminum contacts, the boron implant on the cell back surface may not be essential. The titanium-silver contacts showed definite need for the P^+ interface and also showed that the particular pulse sintering conditions employed were in this case not sufficient.

2.3 Wafer Sizing

The solar cell junction must not extend down the wafer edge to form a connecting path from front to back contact. In the case of the ion implanted cell this requires that the wafer edge be masked during implant or that the finished cell be cut from an oversized wafer. An almost trivial possibility associated with pulse processing which might be of use in a completely automated cell fabrication and array encapsulation facility involves sizing the cell to a scribed pattern by the transient stress wave generated from the implant anneal pulse. Figure 4 shows a 2 1/4 inch diameter silicon wafer diamond scribed on its

TABLE I
CONTACT STUDY SUMMARY

Contact Material	Deposition Temperature	Sintering Condition	Behavior
Aluminum 5 μ	26°C	None	370 mV barrier
	26°C	400°C/5 min.	ohmic
	26°C	Pulsed	ohmic
	250°C	None	ohmic
	250°C	400°C/5 min.	ohmic
	250°C	Pulsed	ohmic
	26°C	None	450 mV barrier
	26°C	605°C/5 min.	60 mV barrier
	26°C	Pulsed	270 mV barrier
Titanium-Silver (0.1 μ - 3 μ)	250°C	None	240 mV barrier
	250°C	605°C/5 min.	70 mV barrier
	250°C	Pulsed	280 mV barrier

A. Scribed Wafer Before Pulse.

B. Wafer After Electron Pulse.

Figure 4. Wafer Sizing Using Transient Stress Wave Induced Fracture.

back surface prior to junction implant and precisely fractured along the scribe pattern by the electron pulse used for the implant anneal.

2.4 Pulsed Electron Beam Development

The electron beams being used for pulsed processing continue to involve a degradation mechanism which causes pulse processed cells to remain 5 to 10% lower in output than similar conventionally processed cells. Finished conventionally processed diffused or implanted junction cells also degrade 5 to 10% (lose 20 to 50 mV of Voc) when subjected to the electron pulse. The effect is attributed to ion contamination of the electron beam which is difficult to eliminate because of the method by which the very high current electron pulse is generated. Necessary correction of the beam contamination problem is being performed under Air Force Aero Propulsion Laboratory Contract F33615-75-C-2006.

As part of the effort to eliminate possible sources of contaminants, the electron beam generation configuration is being modified. An immediate advantageous result has been that the uniform area available in the pulse has been increased from a spot large enough to process a 2 x 2 cm cell to one sufficient to process a 3 inch diameter cell in a single pulse.

2.5 Processing Sequence

In preparation for minimization of processing sequence duration, silicon wafer to finished cell, fabrications are now being timed. Because operations are performed in a number of separate pieces of apparatus rather than in a combined automated facility, handling, transfer and pump-down periods are not clocked. Present times for each operation of existing sequences for fabrication of 2 x 2 cm N^+PP^+ cells using furnace and pulsed electron beam methods are summarized in Table II. Total times for the conventional and pulsed processes are 5423 and 371 seconds respectively. Most of the pulse process total resulted because the ion implanter was set up to scan a 7.6 cm x 7.6 cm area even though the cell being prepared was only 2 x 2 cm. It is now apparent that the program goal of 120 seconds for a 2 x 2 cm cell will be achieved and bettered. If 3 inch diameter cells are produced, processing time will drop from approximately 30 seconds per cm^2 to less than 10 seconds per cm^2 of cell surface area.

TABLE II
PRESENT CELL PROCESS TIMES

A. Conventional Processing	Measured Time	Area Dependent ?
1. Implant $10^{15} \text{ cm}^{-2} \text{ p}^{31+}$	46 sec	Yes
2. Anneal 750°C	2400	No
3. Evaporate $0.1 \text{ } \mu\text{m}$ Al on back	25	Yes
4. Alloy at 650°C	1500	No
5. HF dip and clean	1064	No
6. Evaporate $1 \text{ } \mu\text{m}$ Al back contact	27	Yes
7. Evaporate $5 \text{ } \mu\text{m}$ Al front contact	37	Yes
8. Evaporate SiO_x AR coating	23	Yes
9. Sinter 300°C	<u>300</u>	No
TOTAL	5423	
B. Pulsed Electron Beam Processing		
1. Implant $10^{15} \text{ cm}^{-2} \text{ p}^{31+}$	46	Yes
2. Implant $10^{15} \text{ cm}^{-2} \text{ B}^{11+}$	233	Yes
3. Anneal front with electron pulse	<1	No
4. Anneal back with electron pulse	<1	No
5. Evaporate $1 \text{ } \mu\text{m}$ Al back contact	27	Yes
6. Evaporate $5 \text{ } \mu\text{m}$ Al front contact	37	Yes
7. Evaporate SiO_x AR coating	23	Yes
8. Sinter front with electron pulse	<1	No
9. Sinter back with electron pulse	<u><1</u>	
TOTAL	371	

3.0 CONCLUSIONS AND RECOMMENDATIONS

Development of optimized individual steps of the high rate, low energy expenditure fabrication procedure is progressing satisfactorily. Program goals for processing time and energy consumption are being approached and should be achieved. Cell performance objective of 11% AMO has not been achieved and requires correction of an electron beam problem which is specifically not addressed under this program. Present cell performance capability is 9% AMO.

4.0 APPENDICES

4.1 New Technology

No new technology has been identified during the period of this report.

4.2 Program Plan

An updated program schedule is given in Table III.

4.3 Man Hours and Costs

Total man-hours and costs for period of this report (1 January - 31 March 1976) were 1,724 hours and \$39,712 respectively; from program inception, 3,289 hours and \$75,009.

Table I. Program Schedule.