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

Quarterly Progress Report No. 3

A. R. Kirkpatrick
J. A. Minnucci

July 1976

Work Performed Under JPL Contract No. 954289

Simulation Physics, Incorporated
Burlington, Massachusetts

ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
Division of Solar Energy

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Price: Paper Copy \$3.50 (domestic)
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The work was performed for the Jet Propulsion Laboratory, California Institute of Technology, under NASA Contract NAS7-100 for the U.S. Energy Research and Development Administration, Division of Solar Energy.

The JPL Low-Cost Silicon Solar Array Project is funded by ERDA and forms part of the ERDA Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays.

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**Prepared Under Contract No. 954289 for
JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
Pasadena, California 91103**

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SIMULATION PHYSICS

41 "B" Street, Burlington, Massachusetts 01803

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ABSTRACT

Solar cells are being fabricated by ion implantation and pulsed electron beam techniques which eliminate much of the complexity and energy consumption associated with conventional processing methods. Development continues to progress toward achievement of program objectives.

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1.0 INTRODUCTION

There is little doubt that solar cells are to have future terrestrial power source applications. However the extent to which they can eventually be employed is yet to be determined. If solar cell arrays are to have measurable impact upon satisfying future total energy demands, radically altered production technology will be required. The enormous production volumes and low costs to be associated with a significant contribution to energy need will not be achieved with processing which is slow or wasteful of energy.

The subject program of this report involves development of a method for fabrication of silicon solar cells using a short series of fast operations all performed in a vacuum environment with the silicon material under process held essentially at room temperature. Ion implantation is used for introduction of the device junction. Conventional thermal procedures for implant damage anneal and contact sintering are replaced by transient effects due to momentary energy deposition by a high intensity submicrosecond electron beam pulse. The approach makes feasible cell fabrication in an extraordinarily short time with expenditure of very little energy and without consumable material waste.

Ability to process solar cells using the techniques under development has been demonstrated and discussed in the two previous quarterly reports. Recent effort has involved investigation toward optimization of individual process steps and of overall

cell fabrication sequence. The program has the objectives of demonstrating fabrication of 2 x 2 cm 11% Air Mass Zero efficient silicon solar cells using not more than 120 seconds total processing time and not more than 5 calories/cm² of direct energy transmitted to the surface of the cell under process. Present capability is 9-10% efficient cells and time-energy utilization now meeting objective levels.

2.0 TECHNICAL DISCUSSION

2.1 Pulsed Electron Beams

Use of a pulsed electron beam to perform processing steps which usually require high temperature furnace operations forms the core of the cell fabrication concept. Junction diffusion, ion implantation damage anneal and contact sintering by furnace methods are inherently slow and energy consuming procedures. Ion implant damage anneal and contact treatment can be accomplished by single high intensity pulses of relatively low energy electrons. The electron beam pulse parameters being employed in this program result from separate development under Air Force Aero Propulsion Laboratory Contract F33615-75-C-2006. Present beam parameters are recognized as being not yet optimized.

Electron beams used earlier in this program were found to be contaminated by undesirable ion species originating by vaporization from components of the electron beam generator. Because of configuration of the system, these ions could be accelerated by the drifting electron cloud. On impact with the silicon under process the ions caused an increase in junction generation-recombination current and a consequent loss of open circuit voltage in the finished cell. The effect was nonrecoverable in that subsequent annealing in a high temperature furnace would not increase open circuit voltage toward full value.

The method for utilizing the electron beam has now been altered so that contaminant ion acceleration to a wafer under process is much reduced. Nonrecoverable cell voltage loss is now

a minimum of approximately 5 millivolts as compared to 20-50 millivolts previously. However mean electron energy in this present configuration is very low, less than 20 keV, leading to extremely shallow deposition into the silicon surface. Pulse width of the existing facility is essentially fixed at 10^{-7} second. The combination of low electron energy, extremely short pulse duration and rapid thermal relaxation in silicon causes very high surface temperature to now be maintained for a period apparently slightly inadequate for complete anneal of ion implantation damage. Cell open circuit voltage remains less than complete although additional furnace anneal brings V_{oc} to almost full expectation. Duration of high temperature increases with increasing total energy deposited, but before an adequate condition is reached the silicon surface melts and catastrophic damage occurs. Listed in Table 1 are measured V_{oc} values after pulse anneal of implantation damage on wafer samples which would give 540 mV with furnace anneal. Total deposited energy increases with increasing machine charging voltage. Figure 1 shows calculated temperature versus depth profiles for the highest fluence condition not causing physical damage. It is concluded that electron beam pulse width should be increased from 10^{-7} second to at least 10^{-6} second.

2.2 Ion Implantation

Selection of implant parameters for a terrestrial solar cell involves a number of considerations. For process demonstrations

Table. 1

Cell Voltage Versus Electron Beam Charging Voltage

Increasing Pulse Fluence
↓

Charging Voltage kV	Ion Implant Energy keV	Cell V_{oc} mV
115	25	446-458
125	25	423-456
130	15	481-491
130	10	505-516
135	25	515-519
140	15	502-508
140	10	505-516
145	25	518-521
150	15	Surface fracture
150	10	Surface fracture
150		520-523
>150		Surface fracture

Figure 1. Calculated Temperature Versus Depth Profiles After Electron Pulse in Silicon.

under this program shortest overall processing time will be achieved with junctions formed by P^{31+} implants to 10^{15} ions/cm² at 25 keV. This is a concession to existing equipment, the SPI implanter beam current and throughput decrease rapidly below 25 keV. For eventual production other conditions will certainly be chosen.

Cell junction depth decreases as ion energy is reduced. Cell spectral response at shorter wavelengths should improve as the junction is moved closer to the surface such that more photons will be absorbed in the long lifetime material of the base. Figure 2 illustrates relative quantum efficiency characteristics (collected charge carriers per incident photon) experimentally measured from otherwise identical bare 10 Ω -cm N/P cells with junctions implanted at 20 and 5 keV. Junction depths were roughly 0.25 and 0.1 μ m respectively. Superiority of the shallower junction is evident.

Implant fluence also has effect on quantum efficiency but to a secondary degree. The primary factor in selection of fluence is the interrelationship of resulting sheet resistivity and contact grid to determine cell series resistance. Figure 3 illustrates this relationship calculated for a 2x2 cm cell with aluminum contacts in the 10 finger grid pattern used for cells under this program.

Series resistance of 2 x 2 cm demonstration cells should be less than 0.3 ohm. Nominal thickness of the aluminum contact

Figure 2. Measured Spectral Response of Cells with 20 and 5 keV Junction Implants.

Figure 3. Predicted Cell Series Resistance Versus Junction Implant Fluence.

grid will be 5 micrometers. Figure 3 suggests that implant fluence must be almost 10^{15} cm^{-2} in order to be able to achieve this resistance.

It has been expected that a boron ion implant would be used on the demonstration cell back surface to form a P^+ contact interface underlayer for the N^+PP^+ structure. Because of effort to improve and shorten the processing sequence, it is now believed that the boron implant can be omitted through use of a different contacting procedure.

2.3 Contacts

Producing satisfactory cell front and back contacts of aluminum by cold substrate evaporation onto polished wafer surfaces without special preparation is found to be one of the most difficult tasks of this program. The problem is still being examined.

When an aluminum contact is deposited directly onto the lightly doped base region of an N/P cell and not additionally processed, the contact is nonohmic. Introduction of a heavily doped P^+ underlayer can correct the situation. A boron ion implant with pulsed electron beam anneal has been used for this purpose but a better method is now considered to be formation of a shallow alloyed aluminum-silicon interface by electron beam pulsing.

The cell back contact is nominally one micrometer thick. The present pulsed electron beam deposits most of its energy very close to the surface upon which it impacts. It is presently difficult to produce sufficient temperature for alloying at the silicon-aluminum interface under a one micrometer aluminum layer without causing melting or vaporization of the aluminum front surface. As a result, the back contact is being achieved as follows:

- (1) Evaporate 0.1 μm aluminum on wafer back.
- (2) Pulse alloy using electron beam.
- (3) Evaporate nominal 1 μm aluminum back contact.

Deposition and alloying of the 0.1 μm of aluminum are found to be best performed before implantation of the cell junction. Otherwise the junction becomes reverse biased by the alloying pulse and interferes with propagation of the beam.

In the case of the front contact which is nominally 5 μm thick a sintering rather than alloying pulse is desired. In its present form the electron beam would vaporize the contact surface without elevating the interface to an adequate sintering temperature, perhaps 500°C. A two step deposition with electron pulse between as with the back contact is not convenient because of difficulty in aligning the mask for the second evaporation. A different pulsed energy deposition procedure with less preferential front surface loading should solve the problem. A method is now being sought. In the meantime the front contact can be

deposited directly onto the junction layer and is ohmic even without sintering. However without the sintering step, the contact involves some additional series resistance and somewhat reduced mechanical integrity.

Figure 4 shows an Air Mass Zero I-V characteristics of a cell on which the back contact was deposited as described above, the implanted junction was pulse annealed, and the front contact was deposited without subsequent sintering. No mechanical or chemical preparation was used prior to contact applications. Front contact aluminum was approximately 2 μm thick and measured series resistance of the cell was 0.53 ohm, roughly 0.2 ohm higher than should have resulted if the front contact had been sintered.

2.4 Processing Sequence/Time/Energy Consumption

Cell fabrication sequence at the present time starting with a clean silicon wafer is as follows:

- (1) Evaporate 0.1 μm aluminum on back.
- (2) Pulse alloy with electron beam.
- (3) Evaporate 1 μm aluminum back contact.
- (4) Implant junction: P^{31+} , 25 keV, 10^{15} cm^{-2} .
- (5) Pulse anneal implant damage with electron beam.
- (6) Evaporate 5 μm aluminum front contact.
- (7) Evaporate AR coating.
- (8) Pulse sinter front surface by ?

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Milliamps

Figure 4. Air Mass Zero I-V
Characteristic of Aluminum
Contact Cell Processed With-
out Surface Preparation.

Millivolts

A satisfactory method for the final step sintering of the front contact and antireflection coating has not yet been identified.

Effort has been made to reduce the time required for each process operation to a value consistent with fabricating a 2 x 2 cm cell in 120 seconds. Each process has been individually experimentally speeded up to the necessary degree so that combined total of the separately demonstrated operations has been dropped to 120 seconds. Individual elements are listed in Table II. All of the processes performed actually could be used for cells larger than 2 x 2 cm without increase in time required. To meet the time goal, scan on the ion implanter was reduced from standard 7.8 cm square to a 5.6 cm square. Cell implant time at full beam current was thereby reduced from 51 to 26 seconds.

Calculated direct energy consumptions for each process step and total sequence are also given in Table II. The calculations arbitrarily consider only the energy actually carried to the wafer surface by the ion beam, by an electron pulse or by evaporated coating material. A total of less than the 5 cal/cm² program objective is obtained. This accounting procedure has little absolute significance but does demonstrate the low energy consumption level associated with this processing concept. A 10% efficient solar cell under full 100 mW/cm² terrestrial sunlight outputs 8.6 calories per hour per cm². The direct energy

Table II
Process Times and Direct Energy Utilizations

Process Step	Measured Time	Calculated Direct Energy to Wafer Surface
1. Evaporate 0.1 μm Al on back	4 sec	0.03 cal/cm ²
2. Pulse alloy with electron beam	<<1	0.2
3. Evaporate 1 μm Al on back	27	0.3
4. Implant junction p ³¹⁺ 25 keV, 10 ¹⁵ cm ⁻² at 200 μA	26*	1.0
5. Pulse anneal with electron	<<1	0.2
6. Evaporate 5 μm Al on front	37	1.3
7. Evaporate SiO _x AR coating	23	0.02
8. Pulse sinter front coatings (Process not yet selected)	<<1	~0.2
TOTALS	117 sec	3.3 cal/cm ²

* Implanter scan reduced to 5.6 cm square.

used to process the solar cell from silicon material to finished device should be repaid in less than an hour and gross "at the plug" energy consumed should be recovered in a period of the order of a day.

3.0 CONCLUSIONS AND RECOMMENDATIONS

Individual processes and complete solar cell fabrication sequence for the concept under development continues to progress. Of the major program goals, preparation of cells processed under the time and energy limitations has been accomplished and cell performance level is at present 9-10% AMO as compared to the 11% objective. No inherent limitations to prevent 11% from eventually being reached and exceeded have been observed. The combination of ion implantation and pulsed electron beam processing appears very promising for eventual large scale production.

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 the period 1 April through 30 June 1976 were 1,680 hours and \$38,863 respectively; from program inception, 4,968 hours and \$113,873.

Table III. Program Schedule.