MASTER

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

Final Report

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ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
Division of Solar Energy

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FINAL REPORT
NOVEMBER 1976

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JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA 91103

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Contributions to this program have been made by a number of individuals. The principal investigator was A. R. Kirkpatrick. J. A. Minnucci was responsible for ion implantation and solar cell processing development and for coordination with electron beam processing investigations led by A. C. Greenwald. R. G. Little directed development of electron beam technology and its utilization. The considerable contributions by other technical and support personnel of Simulation Physics and by personnel of Jet Propulsion Laboratory, particularly R. H. Josephs the Technical Manager, are gratefully acknowledged.

ABSTRACT

A one year program to develop a new concept for silicon solar cell production based upon the use of pulsed electron beam processes combined with ion implantation has been completed. Feasibility of producing solar cells at high speed by a simplified vacuum-room temperature processing sequence has been demonstrated. The method has many advantages, particularly for large scale production at lowest possible cost.

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SECTION I INTRODUCTION

This report describes the results of a twelve month program for "Development of Methods and Procedures for High Rate-Low Energy Expenditure Fabrication of Solar Cells". Purpose of the program has been to demonstrate feasibility of an approach to silicon solar cell fabrication which is radical but has promise for extreme reduction of cost, material waste and energy consumption associated with production of silicon solar cells. The effort has been very successful.

1.1 ACCOMPLISHMENTS OF THE PROGRAM

If solar cells are to become competitive for terrestrial power applications, major advances are required in methods to produce high performance cells from whatever low cost silicon material becomes available. Unquestionably the production should be totally automated. In itself this is a difficult problem if conventional concepts for cell fabrication must be utilized. Even with considerable simplification and optimization, conventional techniques cannot avoid ponderous process compositions consisting of operations at varying temperatures in a collection of gas, liquid and vacuum phase environments. An accomplished objective of the present program has been to simplify cell processing to a minimum number of steps all of which can be performed in a common vacuum-room temperature environment.

The area of solar cell device which must be processed even to meet only the interim 1985 solar array production goal of 5×10^8 watts/year is unheard of within the semiconductor industry. If such product throughput is to be achieved by a reasonably small number of facilities of practical size, it will be essential that processing from silicon material to finished device

be fast. This development program has resulted in demonstration of cell fabrication requiring less than two minutes total processing time. Even briefer requirements are projected and these are at least two orders of magnitude shorter than the lower limits expected from conventional methods.

The amount of waste material generated by production processing will have major influence not only upon the cost of terrestrial photovoltaics. Conventional processing technology involves disposal of waste gases, solvent, acids, etc. In massive volumes these expensive wastes would be appreciable environmental hazards. As a consequence of the all-vacuum environment, under the development program of this report, cell fabrication starting with adequate silicon material has been demonstrated to be possible without generation of any waste materials whatsoever.

Even with elimination of waste material, it remains essential from a cost standpoint that cells be produced without the use of expensive material components. Other than the silicon itself, the most costly structural item is the contact mass. A standard silver based contact is excessively expensive but is also technically difficult to replace because of certain considerations of conventional processing. Aluminum contacts are being successfully employed in the present program and the techniques involved should be equally suitable for even low grade aluminum and low cost but usually unacceptable metals such as copper.

It is reasonable to project that solar cells will almost certainly be utilized for certain specialized terrestrial power source applications. However, if they are ever to advance beyond limited use so as to have impact toward satisfying total terrestrial power requirements, it is essential that the energy consumption associated with production of the cells be drastically reduced from existing levels. The processing concept which has been developed

and demonstrated under this program has been shown to reduce device fabrication energy consumption to an almost negligible level such that payback can be made by a few hours of the output of the cell.

1.2 METHOD AND RATIONALE

This new approach to solar cell processing is based around pulsed energy techniques employed in conjunction with ion implantation. Ion implantation itself is not new for solar cell purposes and has in fact been considered as a potential production method for more than a decade⁽¹⁾. Among the advantages which ion implantation can now offer for terrestrial cell production are the ability to affect only the material surface being processed, the ability to introduce junction dopant at room temperature and the possibility for achieving very high processing rates and throughputs.

It is generally considered that the primary disadvantage of ion implantation for junction introduction is the need to anneal radiation damage in the implanted region. Typically anneal requirements involve a high temperature cycle comparable to that used to prepare a junction by diffusion.

Regardless of how the cell junction is produced, it is the high temperature operations of conventional processing, the junction diffusion, the implant damage anneal, the contact sintering steps, which are responsible for most of the time and energy consumption associated with even an optimally simplified conventional production process. Also it is these elevated temperature steps which directly or indirectly determine the consumable material waste due to production.

However, whenever an elevated temperature operation is employed it is for the purpose of treating the vicinity of a surface of the silicon material being processed into a solar cell.

This is true for all the essential procedures related to preparation of a junction or contact underlayer and for the sintering operations for contacts or other surface coatings. Consequently it is in principle possible that all of the thermal operations of cell fabrication could be performed by subjecting individual surfaces only to adequate processing environments.

The approach of this program has been to use pulsed energy techniques to subject specific surface regions to momentary elevated temperature transients. Energy deposition has been by large area pulsed beams of relatively low energy, 15 to 40 keV, electrons. The electrons deposit their energy close to the surface involved and the pulse is sufficiently short, less than a microsecond, that little heat loss can occur from the region during the pulse. Consequently only a small mass of material is heated and very high temperatures can be achieved in the process region using very little consumed energy. Within microseconds the temperature transient decays and the material as a whole is left at room temperature. Satisfactory conditions for anneal of implant damage and sintering of electrical contacts have been achieved. Conventional procedures requiring long periods at high temperatures are replaced by single momentary pulse operations performed on room temperature substrates.

Exploitation of the combined pulse processing and ion implantation capabilities has resulted in demonstration of reasonably high performance cells (>10% AMO) fabricated totally under vacuum and at room temperature. Total process times from silicon wafer to finished cell have been reduced to less than two minutes. Energy utilization by the processing has been shown to have been slashed to the low level objectives of the program.

SECTION II

PULSED ELECTRON BEAM PROCESSING

2.1 METHOD

The basis for producing processing effects by momentary temperature transients is the ability to achieve and then quickly quench a high temperature in the localized region being treated. The method employs a pulsed beam of electrons with mean electron energy under 20 keV and maximum energy less than 125 keV, the threshold for lattice displacement damage in silicon⁽²⁾. Figure 1 shows spectral content of a typical processing beam. Spatial energy deposition profile in silicon for this beam is indicated in Figure 2. Almost all of the energy carried by the electron beam is deposited into the first 2 micrometers of the surface vicinity region being processed. If the electron pulse is short enough that little thermal transfer occurs out of the energy deposition volume during the pulse, then only a small material mass is heated and the pulse energy can be effectively and efficiently utilized to achieve processing effects.

Duration of the electron beam pulse used to date for development work under this program has been 10^{-7} second. Figure 3 shows predicted temperature profiles in silicon at the end of the pulse and at a few instants thereafter. Note that although the electron beam in this case carries only 0.2 cal/cm^2 to the silicon, surface temperature in this case momentarily exceeds 1400°C .

Upon completion of the pulse, the transient temperature profile relaxes with a time constant of the order of a microsecond so that after a number of microseconds the material under process is again at essentially room temperature. It is found that solar cell processes require only single correctly selected pulses.

Figure 1. Energy Spectrum of Pulsed Electron Beam.

Figure 2. Energy Deposition Profile in Silicon for Pulsed Electron Beam

Figure 3. Transient Temperature Profiles in Silicon Following Electron Beam Pulse

Among the many advantages which can be identified with this method of processing is the inability of contaminants to migrate within the semiconductor material because of the extremely short durations over which elevated temperatures are maintained.

Parameters of the electron beam must be carefully selected to achieve desired processing while avoiding deleterious side effects. Development of the electron beam parameters used through this program has been funded under a related Air Force Aero Propulsion Laboratory Contract⁽³⁾. To pulse anneal ion implant damage or activate an electrical contact, certain threshold conditions must be achieved. Due to the complexity of phenomena involved and speed at which they take place these thresholds are somewhat vaguely defined. It has been necessary to combine difficult trial and error variation of electron beam parameters and their observed effects with correlating computer analyses predictions to establish satisfactory techniques.

Among the effects which can occur as a result of inadequate beam parameters and which cannot be tolerated are vaporization or melting of the silicon surface and microfracture of the silicon along crystal planes. It is particularly important to avoid nonhomogeneities in the electron beam which can cause local microscopic occurrence of these problems. Shown in Figure 4 are rather severe examples of effects which can occur under excessive electron pulse conditions. Beam conditions adequate for each required process have been identified which do not cause any of the extraneous physical damage mechanisms. At present uniform beams approximately two inches in diameter are being used. Figure 5 shows the visible signature of such a beam on the surface of an ion implanted silicon wafer.

Because of the manner in which the intense electron pulses are generated and controlled, some generator configurations allow the possibility for ionic contaminants to be injected into the beam

Figure 4A.
Microfracture of
Silicon Surface
Caused by Excessive
Beam Parameters

200 X

Figure 4B.
Local Fracture
and Spallation
of Silicon Sur-
face Due to Non-
uniformity in
Electron Beam

200 X

Figure 4C.
Microscopic Region
of Silicon Melt and
Vaporization Due
to Filamentary Non-
uniformity in
Electron Beam

400 X

Figure 5. Electron Beam Anneal Signature
on Implanted Silicon Wafer

and accelerated by it. In this case the ions also impact upon the surface being processed and will penetrate to depth determined by their energy. When the front surface of the solar cell is being processed these ions can affect junction generation-recombination current. The result is observed as a decrease in solar cell open circuit voltage. Considerable effort has gone into understanding and eliminating the problem. The effect has been greatly reduced and at present involves a loss of less than 5 millivolts (out of 545 mV) in a 10 ohm-cm cell. The electron beam will cause this amount of voltage loss in a finished solar cell subjected to the pulse. Complete elimination is anticipated with further configurational improvement.

2.2 PULSE ANNEAL OF ION IMPLANTATION DAMAGE

Pulse annealing of ion implantation damage requires much higher transient temperatures than does contact sintering. A definite threshold seems to exist below which transient annealing is ineffective. The threshold level has not yet been quantitatively characterized and may involve temperature-time interdependence perhaps with additional factors. Above the threshold some variation in degree of annealing is observed. Best pulse annealed phosphorus ion implants exhibit electrical activation superior to that produced by a conventional 750°C/30 minute furnace anneal. The best pulse anneal conditions apparently involve elevation of the temperature of the implanted region to the melting point of silicon, 1410°C, without supplying heat of fusion to allow the material to liquify. Using a 0.1 microsecond pulse, the single crystal structure is almost fully restored in the implanted material. Experimental studies involving variation of pulse conditions indicate that a longer pulse of perhaps one microsecond might be desirable to extend the duration of incipient melt.

2.3 PULSE TREATMENT OF CONTACTS

In general the electrical contacts deposited onto a silicon solar cell require an elevated temperature sintering step to produce good mechanical adherence and ohmic behavior. Mechanisms involve short range atomic interactions at the metal/silicon interfaces. Conventionally, moderate furnace treatments are used at temperatures below the metal/silicon eutectic.

If transient heating of the contact interface is utilized, equivalent effects are achieved. Using the pulsed electron beam method, duration of temperature elevation at the interface is very brief. As a result it is feasible to use temperatures which exceed the metal/silicon eutectic because, although alloying can begin at the interface, the process is quenched before appreciable inter-solution can occur. During the program the method has been used to successfully demonstrate interfacial alloying of a number of metals with silicon. A specific objective of the program defines contact metallization for the solar cells to be aluminum and accordingly development has emphasized this material.

Evaporated aluminum contacts deposited directly onto polished or etched silicon at room temperature without subsequent treatment are nonohmic. Figure 6 shows dark current-voltage measurements made between aluminum test contact areas on polished 10 ohm-cm silicon. The characteristic between areas receiving pulse treatment is seen to be ohmic while that between a pulsed area and an untreated area indicates rectifying behavior at the untreated silicon aluminum interface. Similar results occur when the aluminum is on a heavily doped junction layer.

Figure 6. I-V Characteristics Between Contact Spots Showing Ohmic Behavior of Pulse Treated Areas.

SECTION III

ION IMPLANTATION

For any semiconductor device application, ion implantation offers excellent control of dopant impurity profile, uniformity and reproducibility. But implantation has special potential for terrestrial solar cell production. Implantation is a vacuum process which is usually performed at room temperature. Also implantation simply introduces isotopically pure dopant directly into the impact surface and does not involve formation of surface oxides or foreign residue which must subsequently be removed. These features make implantation ideally compatible with a simple automatable processing sequence which can be performed completely in vacuum at room temperature.

The other most important possibility of ion implantation is the throughput potential which it will be able to offer. Implantation equipment is only a few years out of the laboratory and is rapidly advancing toward powerful volume capability. Figure 7 shows the Simulation Physics implanter for solar cell work. This is a special version of the most common production facility, now in operation throughout the semiconductor industry. At energies between 25 and 200 keV the machine delivers a scanned phosphorus beam of 200 microamperes over a three inch square at a slide projector type end station. Best solar cell performance is achieved with lower ion energy junctions. Below 25 keV, beam current on this machine falls off linearly. At 25 keV the machine will process roughly 1 cm^2 of cell junction per second. A new standard production machine is now being manufactured which can deliver more than 2 milliamperes of phosphorus at energies between 5 and 200 keV. This machine can process approximately 20 cm^2 of solar cell per second. Neither of these machines has any importance for large scale terrestrial production. Next generation dedicated massive production implanters to be developed by Extrion Corporation

Figure 7. SPI Production Ion Implanter

will deliver continuous 100 milliamperes distributed beams. Solar cell junction throughput of such a facility will approach 1 ft² per second.

In the development program of this report, junction implants for N⁺/P cells were made using P³¹⁺ ions. Figure 8 shows the implant profile predicted from stopping theory for a typical phosphorus ion implant condition at 25 keV and also indicates the actual type of profile obtained. Phosphorus implants into crystal-line silicon are characterized by such "tails" from channeling because of ion scattering into and then along aligned crystal axes. To maximize solar cell output the junction should be very shallow so that more of the rapidly absorbed shorter wavelength photons produce carrier pairs in the higher lifetime material of the cell base. Figure 9 shows relative quantum efficiency versus wavelength characteristics from otherwise identical bare 10 ohm-cm N/P cells with junctions implanted at 20 and 5 keV. Junction depths were roughly 0.25 and 0.14 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 the cell front contact grid to determine cell series resistance. Development work in this program was arbitrarily limited to 2 x 2 cm cells with 10 finger grid pattern aluminum front contacts. Figure 10 indicates predicted series resistance of this cell structure versus junction implant fluence for several grid thicknesses. Series resistance of a 2 x 2 cm cell should be under 0.3 ohm. Consequently using nominal 5 micrometer thick aluminum contacts dictates that implant fluence should be approximately 10¹⁵ ions/cm².

Figure 8. Doping Profile in Silicon for 25 keV P^{31+} Ion Implant

Figure 9. Experimental Spectral Response Measurements
From Cells With 20 keV and 5 keV Junction
Implants

Figure 10. Predicted Cell Series Resistance Versus Junction Implant Fluence

SECTION IV

SOLAR CELL PROCESSING

4.1 PROCESSING SEQUENCE

A primary objective of the program has been to develop and demonstrate an abbreviated processing sequence for fabricating high performance N/P silicon solar cells at room temperature, under vacuum, without generation of any waste materials. A number of process variations were considered.

In order to insure good output performance with aluminum contacts it was originally assumed that special preparation would be required under the back contact to produce an $N^+/P/P^+$ structure. A standard conventional practice involves furnace alloying of evaporated aluminum into the surface using perhaps 650°C for 15 minutes. To be compatible with a low temperature process, work was conducted on the use of a boron ion implant with pulse anneal of the implant region. Development effort showed that this approach would be satisfactory, however a simpler solution was identified. If aluminum is deposited directly onto the lightly doped base region surface of the solar cell and then is pulse processed using correctly selected conditions, a shallow alloyed P/P^+ interfacial region can be produced. This is an advantageous simplification to the total process.

In relation to pulse treatment of contacts, a complicating factor has been encountered which is not inherent but rather is associated with specific capabilities of the laboratory equipment being used for this work. Electron pulse conditions which have been developed primarily for ion implant damage anneal involve extremely shallow energy deposition and temperature profiles which are strongly peaked toward the front surface. Much effort would be required in order to change conditions for each process. In the

case of treatment of an aluminum contact one or more microns thick, the present spatial temperature gradient can result in melting or even vaporization of the aluminum front surface before the silicon-aluminum eutectic (577°C) is exceeded at the interface. For the back contact the problem is avoided by first evaporating a thin 0.1 micrometer thick aluminum layer on the surface, pulse alloying the interface of this material, and then evaporating another micrometer of aluminum to complete the contact. The same approach might be used for the front contact but material is deposited through a mask and it is awkward to align the two deposition layers. Effective pulse sintering of thin layer front contacts has been demonstrated. The available electron beam at reduced fluence has been used for less satisfactory sintering of the entire front contact at thicknesses to 5 μm . Fortunately for the purposes of deliverable cell fabrication an aluminum front contact can be made electrically acceptable by minimal treatment. In production, pulsed beams with different deposition profile characteristics would be used for implant anneal and each contact operation.

Cell fabrication sequence used for deliverable cell preparation starting with a clean silicon wafer is as follows:

- (1) Evaporate 0.1 μm aluminum on back.
- (2) Pulse alloy with electron beam pulse.
- (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 SiO_x antireflective coating.
- (8) Sinter front surface with electron beam.

It might seem unusual that the cell back contact is completed before the junction is introduced. For a cold process such

as this there is no problem in having contact metallization present during junction introduction. However the reason for this particular sequence is that if the junction is introduced and annealed before the back contact is applied, the junction acts to block electron flow during pulse sintering of the back contact. This has been found to complicate propagation of the electron beam and might lead to some local damage effects to the cell.

4.2 PERFORMANCE

Figure 11 shows the Air Mass Zero I-V characteristic of a cell processed according to the sequence listed above. Best cells fabricated to date by this method exhibit efficiencies of over 10% AMO or 12-13% AMI. These cells do not yet have optimized junction profiles, improved antireflective coating, fine grid contacts or back surface fields necessary for full performance optimization. Table I lists the AMO performance characteristics of 100 cells fabricated as deliverable items under this program. The short circuit currents from these cells are equivalent to those from similar ion implanted cell structures prepared using conventional processing methods. Open circuit voltages of the pulse processed cells are within approximately 5 millivolts of those expected using thermal procedures. Cells fabricated without any in-process surface preparation have series resistances which are a little higher than those of similar cells prepared using conventional procedures.

Minor series resistance effects in cells processed according to the vacuum-room temperature only method result because the electron beam sintering conditions employed are obtained by simple variation of the implant anneal conditions and have not been optimized for the purposes. Optimized contact treatment beams involve substantially different parameters which must be achieved with a modified electron beam diode configuration. Also, although the cell fabrication is performed totally in a vacuum sequence, a single piece of

Figure 11. AMO I-V Characteristic of Cell
Fabricated With Ion Implantation/
Electron Beam Processing

Table I

Summary of AMO Performance Characteristics
of 2 x 2 cm Cells Prepared by Ion Implantation
and Pulse Processing as Deliverable Items

Base Resistivity (ohm-cm)	Number of Cells		I _{sc} (mA)	V _{oc} (mV)	P _{max} (mW)	M _{max} %
10	49	Average	126	543	48.5	9.0
		Highest	134	550	52.8	9.8
4	51	Average	127	559	49.7	9.2
		Highest	136	583	56.2	10.4

All cells 2 x 2 cm
Aluminum contacts
SiO_x AR coating

AMO 26°C

equipment in which all operations can be conducted in succession does not exist. Although wafers under process should not be exposed to ambient atmosphere, in fact it is at present necessary to do so between each process operation. The processing concept being demonstrated includes no provision for even the slight surface oxidation effects which can occur in ambient atmosphere but would not be encountered in an integrated process facility.

It is considered that the processing method which has been developed is capable of producing cells with efficiencies at least equalling those which can be achieved by any conventional process scheme. A number of arguments can be made for possibilities of superior performance. In any case, there is no evidence that outputs higher than 15% AM1 will not be achieved from further development.

4.3 PROCESSING TIME

An objective of the program has been to demonstrate that nominal 2 x 2 cm solar cells can be fabricated from silicon wafers in less than 2 minutes. Each process has been individually experimentally speeded up to the necessary degree so that combined total of the separately demonstrated operations reached this goal. Table IIA lists process component times. For purposes of comparison, Table IIB tabulates similar information for conventional processing of a similar ion implanted cell structure. This conventional process is itself probably appreciably shorter than with standard techniques. It might be noted that all of the operations in Table IIA would equally apply to a 2 inch diameter cell instead of the 2 x 2 cm configuration used for demonstration. In the case of a 2 inch cell an area of 26 cm² would be processed with an effective time requirement of less than 5 seconds per cm².

Table IIA

Process Element Times For Fabrication of 2 x 2 cm Cells
By Ion Implantation and Pulsed Processing

Step	Measured Time
1. Evaporate 0.1 μm Al on back	4 sec
2. Pulse alloy with electron beam	<< 1
3. Evaporate 1 μm Al in back	27
4. Implant junction P^{31+} 25 keV, 10 ¹⁵ cm ⁻² at 200 μA^*	26
5. Pulse anneal with electron beam	<< 1
6. Evaporate 5 μm Al on front	37
7. Evaporate SiO_x AR coating	23
8. Electron beam sinter front coatings	<1
TOTAL	117 sec

* Implanter scan reduced to 5.6 cm square.

Table IIB

Process Element Times for Fabrication of 2 x 2 cm Cell
By Ion Implantation and Conventional Procedures

Step	Measured Time
1. Implant junction	26 sec
2. Anneal 750°C	2400
3. Evaporate 0.1 μm Al on back	2
4. Alloy at 650°C	1200
5. Chemically clean surfaces	1064
6. Evaporate 1 μm Al back contact	27
7. Evaporate 5 μm Al front contact	37
8. Evaporate SiO_x AR coating	23
9. Sinter 300°C	300
TOTAL	5081 sec

4.4 PROCESSING ENERGY

Solar cell production by the ion implantation and pulsed energy method will involve greatly reduced energy consumption relative to other methods. For each of the process steps now being used it is possible to determine the "direct" energy consumed, a calculation which arbitrarily considers only the energy actually carried to the wafer surface by the ion beam, electron beam or vacuum deposited coating material. An estimate of "at the plug" energy utilization is somewhat more difficult. However a crude estimate can be made using the observations that: (i) ion implanters can carry roughly 10% of their input energy in the ion beam, (ii) electron beam pulsers can be roughly 50% efficient and (iii) production vacuum coaters utilize roughly 20 calories/cm²/μm for aluminum coatings. Direct and gross energy utilization estimates for cell processing are given in Table III.

A 10% efficient solar cell under full 100 mW/cm² terrestrial sunlight outputs 8.6 calories per hour per cm². The direct process energy contribution indicated in Table III would then be repaid by less than one half hour of the cell output. Gross energy consumed in the process, estimated in Table III as 138 cal/cm², could be repaid by 16 hours of the output of the cell. It must be recognized that these values do not consider the energy which will go into producing the silicon material from which the cell is made.

4.5 PRODUCTION FACILITY

A conceptual drawing of a production facility is shown in Figure 12. Silicon material, wafers, ribbons or sheets, would enter a series of connected vacuum chambers through an interlock and would in turn be transported past each process station and then out through another interlock.

Table III.

Estimates of Direct and Gross Energy Consumption
Associated with Production By Ion Implantation
and Pulsed Electron Beams

	Calculated "Direct" Energy to Wafer Surface	Estimated "At the Plug" Energy Consumed
1. Evaporate 0.1 μm Al on back	0.03 cal/cm ²	2 cal/cm ²
2. Pulse Alloy with electron beam	0.2	0.4
3. Evaporate 1 μm Al on back	0.3	20
4. Implant junction P^{31+} , 25 keV 10^{15} cm^{-2}	1.0	10
5. Pulse anneal with electron beam	0.2	0.4
6. Evaporate 5 μm Al on front	1.3	100
7. Evaporate SiO_x AR coating	0.02	5
8. Pulse sinter front coatings with electron beam	0.2	0.4
TOTALS	3.3 cal/cm ²	138 cal/cm ²

Figure 12. Production Facility Concept

It is assumed that throughput limitation of such a facility would be determined by the ion implant station beam current. A 100 milliamperere implanter would process 600 cm² of cell per second to a fluence of 10¹⁵ ions/cm². On a completely continuous basis this is 1.9 x 10⁶ m²/year. If the facility were to run approximately 50% of the time and produced terrestrial cells of 10% efficiency or better, yearly output would be roughly 10⁸ peak watts of cells.

The production facility is expected to cost something under 2 million dollars to build. To obtain a crude estimate of the cost of producing solar cells in the automated facility, the following is projected for a yearly total of 10⁸ peak watts:

Facility amortization (\$2000 K/3 years)	\$670 K
Power and materials (excluding silicon)	1000 K
Labor	<u>100 K</u>
Total direct cost	\$1770 K

This total amounts to less than \$18 per peak kilowatt of solar cells produced. Note that it does not reflect the cost of silicon or of array assembly.

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SECTION V

CONCLUSIONS

Feasibility of a new concept of solar cell production has been successfully demonstrated. The method is capable of producing silicon solar cells in an abbreviated series of operations all of which are conducted in a vacuum environment at room temperature. The use of extremely short and efficient pulsed electron beam techniques to replace usual thermal procedures makes the approach possible.

For demonstration purposes cells exhibiting as high as 10.4% AMO efficiency have been prepared by vacuum-room temperature operations requiring total time of less than two minutes. In a production facility even higher processing speeds would be possible but probably not necessary.

It has been shown that solar cells can be produced without generation of any waste materials, i.e. without the use of any gases, solvents or acid etching solutions. The only consumables necessary other than silicon are the source of junction dopant for the ion implanter, the cell contact and antireflective coating components and input energy for the facilities.

Total energy consumption associated with the processing method is small. Payback requirements are expected to be as low as a few hours of the output of the cells produced.

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