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DEVELOPMENT OF PULSED PROCESSES FOR THE MANUFACTURE OF
SOLAR CELLS

Quarterly Progress Report No. 2

By
John Minnucci

April 1978

Work Performed Under Contract No. NAS-7-100-954786

Spire Corporation
Bedford, Massachusetts

MASTER

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ABSTRACT

This report describes second quarter results under a program to develop ion implantation and specialized associated processes necessary to achieve automated production of silicon solar cells. The report describes implantation requirements for high efficiency solar cells and presents a process specification for baseline 16% efficient cells. Cell performance comparisons have been made in which junctions were prepared by diffusion and ion implantation. Design efforts for an ion implanter capable of implanting 100 MW_e of solar cell product per year are nearing completion.

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SECTION I

INTRODUCTION

This is the second quarterly report under Contract No. 954786, "Development of Pulse Processes for the Manufacture of Solar Cells", being performed under the Automated Array Assembly Task of the LSA Project. Development over the long term is directed toward an extremely abbreviated production scheme for manufacture of solar cells which precludes use of thermal operations and wet chemistry. Immediate emphasis is upon the major element of the production concept: ion implantation. Ion implantation equipment, ion implantation processes and advanced procedures for annealing of ion implant damage are being addressed.

Under previous contract⁽¹⁾ it was demonstrated that silicon solar cells can be fabricated very rapidly without furnace treatments, wet chemistry or gas atmosphere operations if ion implantation is employed in conjunction with pulse energy techniques. Other studies^(2,3,4) have shown that ion implantation will be economically advantageous for automated production if practical, massive throughput ion implanters can be constructed.

Important questions associated with implantation and implanted solar cells remain. Existing ion implantation facilities have been technically inadequate for simple preparation of high efficiency cells and even the largest machines have had very low solar cell throughput capacities. Performance of ion implanted solar cells has received little attention during recent years and implanted cell efficiencies have fallen behind those associated with the best diffused junction cell technology. Emphasis of this program involves resolution of questions regarding hardware and economics of implantation for automated production and also involves introduction of high efficiency elements such as back layer doping and shallow junctions into the solar cell structure. To support this effort, the first high throughput, dedicated solar cell implanter yet produced was installed and the next generation solar cell implanter is under design. The 3 milliampere/system machine, which is now

operational, has a throughput capacity equal to approximately 1 MW_e of solar cell product per year and the 100 milliampere system being designed will be able to process 100 MW_e of cells per year.

Although ion implantation is expected to become the basis of several candidate approaches to automated solar cell production, the most promising concept involves application of directed energy pulses, of submicrosecond duration, to replace thermal operations in cell fabrication. The most important of these operations is the annealing of ion implant radiation damage in the crystal lattice. The pulse annealing process, which has been shown to produce the necessary recrystallization effect, is being studied as part of this program to establish the best process parameters and to identify the physical mechanisms involved.

In summary, the major components of the program include:

- (i) Installation and operation of a dedicated solar cell ion implanter.
- (ii) Conceptual design of a next generation solar cell ion implanter for automated production.
- (iii) Development of processes for high efficiency ion implanted cell fabrication.
- (iv) Development and analysis of pulse energy solar cell processing.

SECTION II

ION IMPLANTATION FACILITIES FOR SOLAR CELL PRODUCTION

2.1 DEDICATED PROCESS SOLAR CELL IMPLANTER

A dedicated, solar cell implanter has been designed in conjunction with Varian/Extrion Division. The design adapts state-of-the-art implanter equipment technology to solar cell production requirements. Specifically, an end station wafer processor has been selected which utilizes a greater fraction of available beam current to allow a throughput of 300 wafers/hour for junction implants. The machine is capable of operating over a low ion energy range, from 5 to 50 keV, of interest for high efficiency solar cell processing. Other unique features of this implanter which distinguish it from standard implanters include:

- (i) Rotation of the wafer during implantation at one revolution per second. This provides uniform doping of texturized surfaces.
- (ii) Elimination of any shadowed area due to absence of a fixed holding mechanism.
- (iii) Continuous wafer processing rather than batch loading.
- (iv) Magnetic field wobbling of the ion beam to provide necessary implant dose uniformity.

Acceptance tests for the implanter were completed during this quarter. Beam currents are well above the minimum required for end station limited throughput of 300 three-inch wafers per hour as shown in Table I. On a multiple shift basis, this implanter can produce junction implants ($1-2 \times 10^{15}$ phosphorous ions/cm² at 5 keV) at a rate equal to approximately 1 MW_e peak power of solar cell product per year.

Normal operating range for the standard Varian/Extrion high current implanter is from 25 to 200 keV. Standard machine beam currents typically

TABLE I

MINIMUM SCANNED BEAM CURRENTS FOR WAFER PROCESS
END STATION LIMITED OPERATION AT 300 WAFERS/HOUR

Species	Dose (ions/cm ²)	Required minimum Beam Current* (ma)	Machine Design Specifi- cation (ma)	Demonstrated Beam Current (ma)
¹¹ B ⁺	1 x 10 ¹⁵	1.0	0.7	0.9
³¹ P ⁺	1 x 10 ¹⁵	1.0	1.0	4.2
	2 x 10 ¹⁵	2.1	1.0	4.2
⁷⁵ As ⁺	1 x 10 ¹⁵	1.0	1.0	2.5

NOTE:

*These beam currents provide 7 second implants; an additional 5 seconds is allowed for wafer transport.

fall off when beam energy is decreased below 25 keV. Low energy ions are desirable because shallow junction solar cells can be processed without oxides or other surface coating absorbers. Beam focussing and magnetic field scanning systems were specially designed for this implanter for low energy ion beams within the range of 5 to 25 keV. Performance data for the implanter at low energy is shown in Table II. The facility is being used in this mode to address critical questions on applications of high rate ion implantation to automated solar cell production. Many of these questions could not be previously answered because of low beam currents and excessively long implant times per wafer.

Requirements are being identified for dose uniformity for both the junction and back surface field implants. The system uses an external oscillating magnetic field to scan the ion beam over the surface of the wafer. Dose uniformity is a function of ion beam energy, ion species, degree of overscan and scan frequency. Circumferential uniformity is assured under all scanner conditions because of rotation of the wafer during implant. Efforts during the second quarter have emphasized determining implanter scan set-up parameters to achieve varying degrees of uniformity from $\pm 25\%$ to $\pm 5\%$ across the wafer surface. Figure 1 presents a typical implant dose uniformity contour map. Values are within $\pm 4.4\%$ for $\pm 2\sigma$; the distribution is circumferentially symmetric. During the remainder of the program the importance of dose uniformity on cell performance will be assessed.

An example of implant parameters which were previously impractical because of low beam currents is the implant requirement for effective back surface fields. For example, back surface fields have been processed with doses of $5 \times 10^{15} \text{ B}^+ \text{ cm}^{-2}$. The implant time is approximately 16 minutes for a 3 inch wafer with a $50 \mu\text{A}$ beam. The high current machine, with 1 ma of B^+ ions, can complete the implant in 40 sec. Implant parameters which effectively replace conventional aluminum alloy back surface fields have been produced. The advantages of boron implantation over aluminum alloy will become critical for polycrystalline silicon material processing where intergranular alloying is to be avoided.

TABLE II

MEASURED SOLAR CELL IMPLANTER BEAM CURRENTS AS
A FUNCTION OF
BEAM ENERGY

E(keV)	Beam Current (mA)		
	11B^+	31P^+	75As^+
5	0.89	-	-
10	0.89	4.2	2.5
15	0.95	2.4	1.6
20	0.95	2.2	1.2
25	0.96	2.0	1.1
30	0.96	2.0	1.1
35	0.96	2.0	1.1
40	0.96	2.1	1.1
45	0.96	2.2	1.2
50	0.95	2.3	1.2

SHEET RESISTANCE MAP

© SIGNETICS CORP 01-MAR-1978 23:30

U3163 SPIRES PHOS. IMPLANT 25KEV 3×10^{15} WAFER # 1009-3

PARAMETERS:

C.F. = 4.450

FPP SPACING = 0.025

CURRENT = 2100.0

CONTOUR INT. = 1.0000 %

UNPAIRED DATA

Figure 1. Phosphorus Implant
Dose Uniformity Map
for Solar Cell
Implanter.

48.34 OHM/SQ. $\pm$ 4.38 %

2.2 DESIGN OF AN AUTOMATED PRODUCTION IMPLANTER

The implanter described in Section 2.1 can serve immediate needs for implanted solar cell process development. But if implantation is to be practical for use as the central element for automated production to meet the mid-1980 objectives, dedicated machines with higher beam currents and faster throughput characteristics must be developed. The basic engineering design of such a solar cell production implanter is underway. It will operate continuously at delivered beam current levels of not less than 100 milliamperes. The operational characteristics of this 100mA automated production implanter, a conventional high current implanter, and the dedicated solar cell, implanter are compared in Table III. Solar cell product throughput of one automated production implanter machine in full operation will be approximately 100 MW_e peak output per year. In order to conduct this design study, Spire has employed Dr. Peter H. Rose, who is generally recognized as one of the world authorities on ion implanter design and construction.

A set of Functional Requirements for the automated production implanter has been defined to represent the minimum performance objectives. These requirements are summarized in Table IV. The implanter must provide continuous, uniform, reproducible, high volume throughput. The design being developed is conservative with high assurance of meeting all objectives. An artist's conception of the facility is shown in Figure 2.

Reliability is assured by the use of ten ion sources each capable of producing 20 mA of analyzed beam current. Under normal use, no more than seven sources will be in operation. This source redundancy will provide adequate reliability for 24-hour-a-day production. Detailed operational parameters of each source, such as beam current and source start-up and shut-down for periodic maintenance, are computer controlled to provide constant implant dose and continuous duty operation.

Major subsystem components are shown in Figure 3. Operational characteristics and functional requirements have been developed for these as follows:

TABLE III

COMPARISON OF ION IMPLANTATION EQUIPMENT
FOR SOLAR CELL JUNCTION IMPLANTS

Specification	Conventional High Current Implanter (Extrion 200-1000)	State-of- the-Art Solar Cell Process Implanter	Advanced Solar Cell Automated Production Implanter
Process Mode	Batch	Continuous	Continuous
Carrier	None	Cassette	Platen
Phosphorus Beam Current	2mA@25keV	4mA@10keV	100mA@10keV
Beam Utilization Efficiency	3%	15%	83%
Throughput	0.14 M ² /HR	1.4 M ² /HR	180 M ² /HR
Solar Cell Product Per Year	100 KW _e	1 MW _e	100 MW _e

TABLE IV

FUNCTIONAL REQUIREMENTS FOR
AUTOMATED PRODUCTION IMPLANTER
WITH MASS ANALYSIS

PARAMETER	REQUIREMENT
Ion Species:	31p^+ , 75As^+ , 11B^+ (single machine may be dedicated to only one ion)
Ion Energy:	Fixed within the range 10-30 keV (to be defined later)
Beam Current:	Minimum 100 mA 31p^+
Analyzed Beam Purity:	Resolution of 0.5 AMU at Mass 31
Beam Uniformity Reproducibility:	Not worse than $\pm 10\%$ over all material area processed
Substrate Throughput:	Variable - minimum of $500 \text{ cm}^2/\text{sec}$ at a dose of $1 \times 10^{15} \text{ ions/cm}^2$
Materials to be Handled:	Silicon wafers, ribbon, sheet, etc. to maximum individual item dimensions 20 x 20 cm
Surfaces to be Implanted:	Planar and texturized
Processing Mode:	Continuous flow
Operational Mode:	Continuous throughout, predictable component lifetime and routine maintenance

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Figure 2. Conceptual Design of a 100 mA Automated Production Implanter.

Figure 3. Schematic of Major Subsystems for an Automated Production Implanter.

Transport Subsystem

The substrate material, not to exceed 20 cm x 20 cm in size, will be loaded onto carriers on two converging conveyors at the entrance to the implanter. The carriers enter a vacuum lock one at a time every half second. After irradiation by the ion beam in the process chamber, the carriers and substrate material exit by an inline system essentially the same as that by which it entered. Motion is imparted to the carriers by constant speed drive motors. All motions are vibration free to avoid damage to the silicon.

Vacuum Subsystem

The vacuum subsystem has to meet the following criteria:

- (i) It must satisfy the requirements of the entrance, implant and exit chamber volumes of the implanter.
- (ii) It must be automatic, operation fault free, reliable, with adequate redundancy, and ease of maintenance.
- (iii) The vacuum system can be separated into three major regions:
 - (1) The entrance and exit systems require fast pumps to bring the gas pressure from ambient to less than 10^{-5} torr. This must be done without vibration of the silicon material.
 - (2) The pumping required for the ion sources and analyzer chamber where there is source gas flow.
 - (3) The process chamber must have adequate pumping to remove the gas generated from cassetts and silicon during implantation. It can be assumed that the entrance and exit systems do not contribute significantly to this load.

Ion Sources

The implanter requires ten ion sources each capable of producing 20 mA of analyzed beam current. Under normal conditions no more than seven sources will be in use. This source redundancy will provide adequate reliability for 24 hour a day operation. A cross-section of a representative ion source design is given in Figure 4.

Analyzer Subsystem

The ion beams from the sources are to be mass analyzed so that only one ion species is accelerated to the wafer target. The analyzer is a large electromagnet configured in two sections with each section analyzing the output of five sources. The magnet pole face gap is 6 cm.

Power Supply Subsystem

Power supplies are required for operation of the ion sources and the electromagnet. Each ion source requires individual arc, filament and extraction power since each source is independent except for coupling through the control system and analysis. Source power supplies must be variable. The electromagnet requires a power supply which can be run at three different current levels to analyze of beams of B^+ , P^+ , or As^+ . Many other power supplies will be used to operate vacuum gauges, controls, etc.

Control Subsystem

The control subsystem is designed to provide fully automatic start up and operation. Furthermore, data logging will be implemented at two levels for a permanent record of information important to solar cell manufacture and a more detailed machine operational record for diagnostic purposes. Operations will generally be controlled through a keyboard, but where appropriate, dedicated displays and individual regulation will be provided. Appropriate software will integrate the logic and control system.

Figure 4. High Current Ion Source Cross Section.

Facility Requirements

The size and weight of the solar cell implanter will be compatible with a typical semiconductor production area. The power, cooling and other requirements will be met by standard industrial facilities. Facility requirements and overall dimensions are given in Figure 5.

Operating costs have been estimated for this design of a 100mA automated production ion implanter. This operating cost estimate is based on the facility requirements outlined in Figure 5, a throughput of 180 m²/hour and three operators/technicians. Average direct costs (no overhead or general and administrative expenses) per hour are estimated below:

Direct Labor:

Supervision, operation and routine maintenance	\$ 30/hr.
Special maintenance	3

Direct Materials:

Electricity, source gas, nitrogen	32
-----------------------------------	----

Maintenance Materials:

Ion source parts, conveyor system components, carriers, vacuum components, pump oils	10
--	----

Total Direct Labor and Materials:	\$ 75/hr
-----------------------------------	----------

Based on a total operating cost of \$75/hr. and a throughput of 180 m²/hour (18KW_e/hour), the direct cost is \$0.004 per peak watt.

TOTAL WEIGHT : 23.5 TONS (21,000 Kg)

MAGNET WEIGHT: 10 TONS (9070 Kg)

FACILITY REQUIREMENTS:

- POWER - 200 kVA MAX., 3 PHASE
4 WIRE, PLUS GROUND
- WATER - 75 PSIG (5 Kg/cm²) MAX.
40 PSIG (2.8 Kg/cm²) MIN.
DIFFERENTIAL BETWEEN INLET
AND OUTLET 35GPM (140 L/sec)
60-80°F (16.27°C) MAX.
INLET TEMPERATURE
- COMPRESSED
AIR - 60-100 PSIG (4.7-7 Kg/cm²)
FOR PNEUMATIC VALVES
- DRY NITROGEN-4.0CFM (1.9 L/sec)
ENTRANCE AND EXIT
- VENTILATION -1200 CFM (565 L/sec)
(toxic gases) EXHAUST

Figure 5. Facility Requirements and Overall Dimensions for an Automated Production Implanter.

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SECTION III

SOLAR CELL DEVELOPMENT

3.1 OBJECTIVES

In order to assess and advance the technical status of ion implantation for silicon solar cells and to integrate implantation processing into a simplified approach for automated production of the highest efficiency cells, the following tasks are being performed under this program:

- (i) Improvement of cell design structure and performance using implantation for n^+ and p^+ dopant introduction
- (ii) Assessment of relative performance of otherwise identical cells with diffused and ion implanted junctions
- (iii) Integration of high performance cell structures into an abbreviated implantation/pulse energy processing sequence being developed for low cost automated production.

3.2 ION IMPLANTATION PARAMETER SELECTION

3.2.1 Junction Layer for $n^+ p p^+$ Structures

Selection of implant parameters for junction introduction is one of the critical design elements for high efficiency solar cells. The parameters are interdependent with subsequent annealing processes and contact grid design. Because implant parameters are flexible, both concentration and dopant location can be easily controlled; however, implanted dopant profiles are quite different than stopping theory predictions.

Desirable characteristics of a solar cell junction layer are quite well known. These are summarized below and in Figure 6:

- (i) A relatively shallow junction is necessary for good blue response. Typically the desired junction depth is from 0.1 to $0.3 \mu m$ for highest efficiency. Either phosphorus ($^{31}P^+$) or arsenic ($^{75}As^+$) can be used as an n-type dopant with implantation. Arsenic has an

Figure 6. Junction Implant Profile for n^+pp^+ Cell Structure.

inherent advantage over phosphorus for producing shallow junctions because its larger atomic size results in less penetration. However, more experimental effort has been carried out to date with phosphorus implantation, in part because successful annealing of the implantation damage has been achieved.

- (ii) The peak dopant concentration should fall continuously from the surface. In practice, this is quite difficult to accomplish without using oxide or nitride layers as preabsorbers. However, these layers can result in knock-on oxygen or nitrogen implants. Furthermore, the use of an absorber increases the implant dose required and reduces implanter throughput.
- (iii) Retrograde fields in depth must be avoided. It is necessary to minimize the channeling of ions along crystal axes which can produce a second peak in the implanted/annealed dopant profile. A severe case of channeling is shown in Figure 7. Reduction of channeling is achieved by intentionally misaligning the ion beam and the silicon wafer by 7 to 15°.

3.2.2 Back Surface Layer for $n^+ p p^+$ Structures

Selection of implant parameters for back surface layers depends upon other cell design requirements. For silicon resistivities greater than $10\Omega\text{-cm}$ with high minority carrier lifetime, the p^+ layer can act as a high-low junction or back surface field (BSF). For lower lifetime silicon of $1.0\Omega\text{-cm}$ resistivity, the p^+ layer only provides a heavily doped layer for ohmic contacts.

Choice of the implanted p^+ ion species depends on its intended function. For BSF's, either $^{11}\text{B}^+$ or $^{27}\text{Al}^+$ ions are effective with proper annealing procedures. For simple ohmic contact $^{11}\text{B}^+$, $^{27}\text{Al}^+$ or $^{49}\text{BF}_2^+$ can be used. The advantage of $^{49}\text{BF}_2^+$ molecular ions is that higher beam currents and therefore higher throughputs can be realized.

Figure 7. Highly Channeled Implant Junction Profile.

A measured boron impurity profile after annealing is shown in Figure 8. Because the depth of implanted ions and the p-p⁺ junction location does not necessarily have to be shallow in this case, higher ion energies are used. However, as with junction implants, channeling must be avoided to prevent retrograde electric fields. A second requirement is the desirability to maintain the peak dopant level at or near the back surface. Both channeling and surface dead layer due to retrograde fields can be minimized by selecting a relatively high anneal temperature which redistributes the implanted boron ions by diffusion.

3.3 ION IMPLANTATION DAMAGE ANNEALING

Successful device optimization requires adequate annealing of the ion implantation induced crystal lattice damage. The characteristics of the lattice damage depend on the implant energy, dose, and temperature of the substrate during implantation. Three generalized cases with different annealing requirements can be distinguished. These are shown in Figure 9 and summarized below:

Low Dose Implants:

For some semiconductor devices the implant dose is less than 10^{14} ions/cm². This level results in isolated defect clusters. Effective annealing can occur by epitaxial regrowth from the surrounding undamaged silicon at very low temperatures. Under some conditions, the damage can be annealed during implant by using elevated substrate temperatures, usually about 500°C.

Intermediate Dose Implants:

Solar cell implants fall within this range of approximately 10^{15} ions/cm². At these levels, localized crystalline nucleation sites remain within the heavily damaged amorphous layer. As a result, competition exists between epitaxial regrowth from the unimplanted single crystal substrate and these localized nucleation sites. This can cause polycrystallite formation, detrimental to cell performance, if only simple annealing procedures are followed.

Figure 8. Backsurface Implant Profile for n^+pp^+ Cell.

LOW DOSE

HIGH DOSE

INTERMEDIATE DOSE

Figure 9. Typical Implant Damage for Various Implant Dose.

High Dose Implants:

Depending on the ion species, doses higher than 5×10^{15} to 1×10^{16} can produce a totally amorphous layer, providing the wafer temperature is not allowed to rise during implant causing polycrystalline regrowth. Temperature increases can result from the large amount of energy deposited during high-current, high-energy implants. Starting with completely amorphous material, well controlled, single crystal, epitaxial regrowth from the undamaged substrate through the implanted amorphous layer can be made to occur. The regrowth rate depends on the anneal temperature. Commonly these temperatures are within 550 to 850°C.

Optimum solar cell implant parameters, as were described in Section 3.1, fall within the intermediate dose range. As such, careful procedures are necessary to produce minimum defect implanted layers. If the required solar cell ion dose is implanted with liquid nitrogen cooling of the wafer, completely amorphous layers can be produced, making good epitaxial regrowth easier; however, such low temperature implants are not amenable to automation.

Requirements for annealing room temperature implants can be summarized as:

- (i) To restore the silicon crystal lattice while minimizing defect sites which increase minority carrier recombination rates.
- (ii) To activate the implanted dopant ions for achieving the required sheet resistance, by causing them to take positions within the crystal lattice.

This must be achieved while:

- (iii) Maintaining a shallow junction depth for adequate blue response,
- (iv) Preserving or enhancing the bulk silicon minority carrier lifetime.

Much effort has been expended in developing furnace annealing parameters that promote single crystal epitaxial regrowth and minimize defect concentration. Figure 10 is a helium ion backscattering and channeling analysis for

Figure 10. Helium Ion Backscattering and Channeling Analysis of Implanted and Annealed Layer(s).

multiple step furnace anneals showing resultant lattice structure⁽⁵⁾. The absence of back scattering signal is due to channeling, which depends upon the quality of the regrowth. The data shows that better lattice recovery results from multiple step anneals. Multiple step annealing schedules have been developed, such as the following:

- (i) First Step Anneal: Temperature range between 450 and 600°C; times of one hour. The purpose of this step is to cause slow single crystal epitaxial regrowth to occur. Figure 11 shows typical regrowth rates for <100> and <111> oriented silicon.⁽⁶⁾
- (ii) Second Step Anneal: Temperature range between 800 and 900°C; times of 15-30 minutes. This step causes substitution of the dopant atoms into the lattice and allows minor redistribution of the as-implanted dopant concentration.
- (iii) Third Step Anneal: Temperature range between 450 and 550°C; times of one hour. This anneal causes bulk lifetime recovery by complexing any residual defects, such as point defects, to carbon or oxygen impurities inherent in any silicon.

Development and optimization of any particular anneal schedule requires consideration of heating and cooling rates between anneal steps.

3.4 ANNEAL OPTIMIZATION FOR SOLAR CELL IMPLANT PARAMETERS

Using the annealing approach summarized above, a test matrix for optimization was designed in which 1 and 10 Ω -cm <100> Czochralski and float zone materials were used. Test procedures consisted of 60 minute isochronal first step anneals at either 450° or 550°C; and 30-minute high temperature second step anneals over a range of 650 to 850°C using a new specimen at each 50°C temperature increment. This second step anneal approach differs from earlier attempts by others in which the same samples were used for progressively higher temperatures steps. In effect, these earlier schedules were equivalent to two, or more, step anneals. Results from the optimization test matrices, as shown in Figures 12 and 13, indicate that a final 450 to 550°C anneal does not change the sheet resistance following a second high temperature anneal, for either

Figure 11. Epitaxial Regrowth Behavior for Implanted Layers at 550°C .

Figure 12. Isochronal Annealing of 10 Ω -cm CZ Silicon.

Figure 13. Isochronal Annealing of 1 Ω -cm CZ Silicon.

the 1 or 10 Ω -cm Czochralski silicon. It was also determined as shown in Figures 14 and 15 that the final junction depth is not significantly deeper if 450 to 550°C, 1-hour first step anneals are used.

3.5 CELL PROCESS COMPARISONS

The first of three cell junction performance assessments is complete. The study has been performed to compare ion implantation and diffusion technologies for dopant introduction. The starting material was <100>1.0 Ω -cm Czochralski silicon with bright etched surfaces. Three groups of cells having both implanted and diffused junctions were processed as follows:

Type I: Diffused junctions and alloyed aluminum p^+ layer introduced at OCLI.

Type II: Ion implanted/furnace annealed junctions and alloyed aluminum p^+ layers introduced at Spire.

Type III: Ion implanted/pulse electron beam annealed junctions and alloyed aluminum p^+ layers introduced at Spire.

For all three types of processing, contacts, multiple layer AR coating, and AMO performance measurements were completed at OCLI. Table V summarizes peak, mean, and standard deviation of AMO efficiencies, for each type. Figures 16 through 24 show the performance distributions of each. Note that the highest short-circuit currents were attained with the ion implanted junctions. However, the results so far show lower cell efficiencies for implanted and pulse or furnace annealed cell processes than for diffused junctions. The lower efficiencies are due to series resistance limited curve factors and not lower I_{sc} or V_{oc} . The higher series resistance for the implanted cells is a result of the mismatch between the OCLI contact design (4 lines/cm) and the implanted junction sheet resistance of 120 ohms per square. Subsequent process comparisons will use a violet cell grid design (10 lines/cm) to preclude this problem.

Figure 14. Junction Depth as a Function of Temperature for Single and Two Step Anneals of 10 Ω-cm CZ.

Figure 15. Junction Depth as a Function of Temperature for Single and Two Step Anneals of 1 Ω-cm CZ.

Table V
SUMMARY OF FIRST PERFORMANCE COMPARISON
OF CELL JUNCTION FORMATION TECHNIQUES

Junction Formation	AMO Efficiency (%)		
	MEAN	PEAK	σ (%)
Diffused	12.1	12.9	0.4
Implant/Furnace Anneal	11.5	12.5	0.6
Implant/Pulse Anneal	11.0	12.3	0.8

NOTES:

Silicon: 1 Ω -cm <100>CZ
Bright Etched Surfaces
300 m thick

Cell Structure: Alloyed aluminum p⁺ layer
TiPdAg Contacts
Multi-layer AR Coating

Figure 16. Distribution of Maximum Power for Diffused Junction Test Cells.

Figure 17. Distribution of Maximum Power for
Implanted/Furnace Annealed Test Cells.

Figure 18. Distribution of Maximum Power for Implanted/Pulse Annealed Test Cells.

Figure 19. Distribution of I_{sc} for Diffused Junction Test Cells.

Figure 20. Distribution of I_{sc} for Diffused Implanted/Furnace Annealed Test Cells.

Figure 21. Distribution of I_{sc} for Implanted/Pulse Annealed Test Cells.

Figure 22. Distribution of V_{oc} for Diffused Test Cells.

Figure 23. Distribution of V_{oc} for Implanted/Furnace Annealed Test Cells.

Figure 24. Distribution of V_{oc} for Implanted/Pulse Annealed Test Cells.

3.6 ION IMPLANTED CELL PERFORMANCE STATUS

A baseline n^+pp^+ solar cell process has been identified which includes implant parameters, furnace annealing conditions, and contact mask design. The process uses $10\ \Omega\text{-cm}$ $\langle 100 \rangle$ Czochralski material and a near optimum furnace anneal schedule. The p^+ layer provides an effective back surface field which increases V_{oc} to 600 mV. The front contact, as presented in the first quarterly report, was designed specifically for implanted junction layer characteristics. The metallization system is CrAuAg. Experience with this contact metallurgy and mask design indicates that ultimate line widths of $25\ \mu\text{m}$ can be fabricated. This will allow nearly ideal performance of the solar cell structure to be achieved. Preliminary cell lots with this contact and implanted n^+pp^+ cell structures have resulted in efficiencies of 14.0% AMO (16.0% AM1), before encapsulation, as is shown in Figure 25. An additional 3 to 5% gain in cell efficiency will be obtained after encapsulation due to improved optical coupling. The process specification used is given in Table VI. It is the baseline process and will continue to be used in developing final detailed anneal schedules.

Figure 25. AMO-25°C Characteristic for Baseline n^+pp^+ Ion Implanted Structure.

Table VI
 BASELINE PROCESS SPECIFICATION FOR ION
 IMPLANTED N^+PP^+ HIGH EFFICIENCY SOLAR CELLS

<u>Silicon Material</u>	10 ohm-cm <100> CZ p-type Surfaces: Front - Polished Back - Bright Etched
<u>Process Sequence</u>	
Implant:	Junction - $2 \times 10^{15} \text{ } 31p^+/\text{cm}^2$, 5 keV, 10° , Back Surface Field - $2 \times 10^{15} \text{ } 31p^+/\text{cm}^2$, 25 keV, 10° ,
Anneal:	Simultaneous phosphorus and boron implant anneal in nitrogen 550°C - 2 hours 850°C - 15 minutes 550°C - 2 hours
Clean:	Buffered HF DI rinse
Front Metallization:	Evaporate $400 \text{ \AA}$ Cr + $400 \text{ \AA}$ Au Define Spire Starburst pattern with standard Kodak KTFR process Electroplate $12 \mu\text{m}$ Ag
Clean:	Buffered HF DI rinse
Back Metallization:	Evaporate $400 \text{ \AA}$ Al + $1 \mu\text{m}$ Ag
AR Coating:	Evaporate $700 \text{ \AA}$ TiO_2
Sinter:	400°C - 10 minutes in nitrogen
Test:	AMO I-V

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SECTION IV

PULSE ENERGY PROCESSING STUDIES

4.1 OBJECTIVES

The application of ion implantation to solar cell processing requires an annealing technique to remove inherent radiation damage of the silicon lattice. As discussed in Section 3.2, the requirements for successful furnace annealing are dependent upon implant parameters. Another approach to annealing ion implantation damage is to utilize pulse energy deposition. In this technique, a pulse energy source is directed onto the surface to be heated. Almost all of the energy carried by these pulsed sources is deposited into the first few microns of the surface being processed, resulting in momentary, high-temperature transients. A mechanism which can explain annealing effects obtained by pulsed energy transients was identified and described in the first quarterly report. Pulse energy sources such as electron and laser beams can replace thermal operations ordinarily performed in a furnace.

4.2 ADVANTAGES OF DIRECTED ENERGY PULSE PROCESSING

The potential advantages of directed energy pulse processing can be separated into technical and cost categories and summarized as follows:

Technical Advantages:

- (i) Higher efficiency cells may be achievable. Better lattice regrowth occurs with pulse annealing as will be discussed. Rapid dopant diffusion during anneal may result in a better junction profile. During pulse processing, the bulk silicon is never brought to a high temperature, thereby precluding lifetime degradation by thermally induced defects.
- (ii) Pulse processing may prove advantageous for fabricating cells from advanced polycrystalline sheet materials. Transient, surface heating will minimize grain boundary effects such as the diffusing of dopants and contact metallization. Also, thermally unstable materials and substrates can be processed.

- (iii) Pulse annealing facilities, analogous to ion implantation facilities, are amenable to in-line processing for automation. Also, pulse annealing is a vacuum process and is compatible with ion implantation equipment.

Economic Advantages:

- (iv) The cost of pulse processing should be considerably less than conventional processing, because no wet chemistry or forming gases are required. Furthermore, pulse processing is an efficient use of input utility supplied power significantly reducing solar cell pay-back time.
- (v) Capital equipment costs for pulse processing will be less than those associated with diffusion processing or ion implantation with annealing furnaces. Since the projected size of a pulse annealer is comparable to a 100 mA implanter, relatively small building space is required. In-line annealing should also reduce the number of silicon carrying cassettes thereby reducing cost.
- (vi) Since the process is amenable to automation and compatible with ion implantation, common cassettes can be implemented.
- (vii) Reduced capital equipment requirements allow production scale up to be achieved relatively easily.

Other Advantages:

- (vii) Reduced environmental impact can be expected due to the elimination of wet chemistry, forming gas processes, and waste treatment facilities.

4.3 DETERMINATION OF FRACTURE THRESHOLDS

Pulse energy processes utilizing either laser or electron beams approach energy deposition thresholds that can cause permanent damage effects in silicon. Such damage effects include microfracture, melting and spalling. Microfracture

results from excessive thermal gradients which can exist within the first few microns of the surface if pulse beam energy is excessive.

Microfracture thresholds have been determined for both $\langle 111 \rangle$ and $\langle 100 \rangle$ oriented silicon. As shown in Table VII, the measured fracture thresholds are close to the beam fluence levels for implant anneal. It is important to note that the microfracture thresholds reported in the table are valid only for a specific set of electron beam characteristics presently being developed. This beam is characterized by a pulse duration of 0.1 microsecond and a mean electron energy of 12keV. Different fracture thresholds would result from different beam conditions.

4.4 PROPERTIES OF PULSE ANNEALED IMPLANTED JUNCTIONS

Phosphorus, arsenic, and boron implanted junctions have demonstrated superior structural quality after pulse annealing compared to optimized furnace annealing. Structure evaluations have been performed by S. S. Lau of California Institute of Technology for Spire. The evaluations were based on helium ion backscattering and channeling and transmission electron microscopy (TEM) analyses. Both backscattering and TEM analyses of pulse annealed implants show that the recrystallized implanted layer is defect free. Typical backscattering and TEM results were presented and discussed in the first quarterly report.

The best implanted structures achieved to date, as defined by the absence of dislocation networks or interstitial atoms, have been obtained by pulse electron beam annealing and combined pulse electron beam and low temperature furnace anneals. Studies have been completed to evaluate and compare dislocation densities of ion implanted silicon wafers after furnace and pulse annealing. The material used included FZ and CZ grown $\langle 100 \rangle$ silicon. Following $2 \times 10^{15} \text{ }^{31}\text{P}^+ \text{ cm}^{-2}$, 5 keV implants, the wafers were annealed by optimized furnace schedules and pulse electron beam.

TABLE VII

MEASURED FRACTURE THRESHOLDS FOR PULSED
ELECTRON BEAM PROCESSING

Threshold	Silicon Orientation	
	<111>	<100>
Microfracture of Unimplanted Wafer	$0.22 \pm 0.02 \text{ cal/cm}^2$	$0.30 \pm 0.03 \text{ cal/cm}^2$
Microfracture of Junction Implanted Wafer	$0.27 \pm 0.03 \text{ cal/cm}^2$	$0.30 \pm 0.03 \text{ cal/cm}^2$
Implant Anneal	0.2 cal/cm^2	0.2 cal/cm^2

Silicon: 7.6 cm diameter
300-500 μm thick

Implant: $2 \times 10^{15} \text{ }^{31}\text{P}^+ \text{cm}^{-2}$, 10keV

Measurement techniques for assessing the quality of the epitaxially regrown implanted/annealed junctions have included: preferential etching to delineate dislocation networks; helium ion backscattering; and transmission electron microscopy. The dislocation density below the surface was also determined by repetitive anodic oxidation and layer stripping techniques. Results of these measurements are shown in Figure 26. Important conclusions for furnace and pulse annealed implants are summarized below:

- i) Furnace annealing results in a dislocation density of about $10^8/\text{cm}^2$ at the wafer surface with a gradual reduction toward the metallurgical junction. This is due to slow regrowth from the unimplanted base material. No evidence was found that implantation induced defects propagate beyond the projected ion range after optimized furnace annealing.
- ii) Pulse annealing results in a decreased dislocation density even when compared to the unimplanted CZ or FZ material. No evidence was found that implantation induced defects remain in the implant region or propagate to the underlying substrate after pulse annealing.

Both laser and electron beam pulse annealed ion implanted cells have typically exhibited a 20 mV lower V_{oc} than furnace annealed implanted cells or diffused cells of the same silicon resistivity. However, the 20 mV degradation has been restored by a low-temperature, post-pulse anneal in the range of 400°C to 500°C. This is typical of lattice point defect annealing requirements.

Point defects remaining in the implanted/pulse annealed layer can be due to incomplete annealing during the rapid recrystallization which occurs within microseconds. It is possible that such rapid regrowth can result in dislocation-free material with excellent structural characteristics, but possess residual point defects due to remaining stresses. Point defects are not detectable by TEM or backscattering techniques. However, they do introduce electronic levels in

Figure 26. Characterization of Defect Density as Measured by Preferential Etching and Anodic Oxidation/Layer Stripping.

the bandgap which increase carrier recombination. These higher recombination rates increase diode leakage currents and, as a result, decrease V_{oc} under illumination. Transient capacitance analysis has been used to determine trap energy levels within the bandgap but such measurements are difficult.

Additional electronic properties of implanted/pulse annealed junction layers have been determined. Both laser and electron beam pulse annealed junction solar cells exhibit higher average short circuit currents when compared to implanted/furnace annealed cells. This effect was demonstrated in the cell process comparisons of Section 3.5. Higher average short circuit currents may be related to more complete electrical activation of the implanted dopant. Fewer interstitials remaining after annealing result in a decreased recombination center density in the junction layer.

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SECTION V

SUMMARY

This report has described the second quarter results of a program whose purpose is to develop ion implantation and associated processing for automated production of solar cells. Significant accomplishments during this reporting period include:

- i) A dedicated solar cell implanter has been operational for three months. Ion beam currents are well above those required for junction implant throughputs of 300 three-inch wafers per hour.
- ii) The design specification for a 100 MW_e/year automated production ion implanter is near completion. Functional requirements for the 100 mA implanter and for major subsystems have been determined. Direct operating costs for junction implants with this facility have been estimated to be \$0.004 per peak watt.
- iii) The performance status of ion implanted solar cells has been advanced. Ion implanted n⁺ pp⁺ cells with efficiencies of 14% AMO (16% AMI) have been achieved. Further efforts are expected to improve these efficiencies to 17% AMI.
- iv) Pulse energy process applications have continued to be investigated. Advantages of pulse annealing include the potential for higher cell efficiencies and its ability to be integrated into an automated ion implantation production process.

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SECTION VI
NEW TECHNOLOGY

No new technology has been developed to completion during this quarter.

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