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DOE/JPL/954786-1

DEVELOPMENT OF PULSED PROCESSES FOR THE MANUFACTURE OF
SOLAR CELLS

Quarterly Progress Report No. 1

By
John Minnucci

January 1978

MASTER

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

Spire Corporation
Bedford, Massachusetts

U.S. Department of Energy

Solar Energy

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Prepared for:

JET PROPULSION LABORATORY
California Institute of Technology
Pasadena, CA 91103

Prepared by: John H. Hines
Principal Investigator

Approved by: All R. Kibben
Program Manager

SPIRE CORPORATION
Patriots Park
Bedford, MA 01730

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ABSTRACT

This report describes first quarter results under a new program to develop ion implantation and specialized associated processes necessary to manufacture implanted silicon solar cells. The report describes ion implantation requirements and ion implantation equipment status. A new dedicated solar cell process ion implanter is now operational. Design work on an implanter capable of implanting roughly 100 mW_e of solar cell product per year is in progress. The report describes the technical status of ion implanted solar cell development. Pulsed energy processes used for annealing of ion implantation damage are described. The mechanism of pulsed energy annealing is presented.

TABLE OF CONTENTS

<u>SECTION</u>	<u>PAGE</u>
I INTRODUCTION	1
II ION IMPLANTATION FACILITIES FOR SOLAR CELL PRODUCTION	5
2.1 GENERAL CONSIDERATIONS	5
2.2 DEDICATED PROCESS SOLAR CELL IMPLANTER	12
2.3 DESIGN OF AUTOMATED PRODUCTION IMPLANTER	22
III SOLAR CELL STUDIES	27
3.1 OBJECTIVES	27
3.2 IMPLANTED CELL PERFORMANCE STATUS	28
3.2.1 Planar Surface Cells	28
3.2.2 Texturized Surface Cells	31
3.2.3 Cast Polycrystalline Sheet Cells	33
3.2.4 Pulse Annealed Cells	36
3.3 CONTACT DESIGN	37
IV PULSED ENERGY PROCESSING STUDIES	47
4.1 GENERAL	47
4.2 MECHANISM OF THE PULSE ANNEAL PROCESS	53
V CONCLUSIONS	63
VI NEW TECHNOLOGY	65
REFERENCES	67

LIST OF ILLUSTRATIONS

<u>NUMBER</u>		<u>PAGE</u>
1	Typical Implanter Configuration	6
2	Phosphorus Ion Profiles in Silicon	9
3	Arsenic Ion Profiles in Silicon	10
4	Standard, Medium-Current Production Ion Implanter	13
5	Dedicated Solar Cell Process Implanter	15
6	Dedicated Solar Cell Process Implanter Ion Source	16
7	Wafer Rotation/Holder for Solar Cell Implants	20
8	Components of Automated Production Implanter	24
9	Air Mass Zero I-V Characteristic of Test Cell From Solar Cell Process Implanter	30
10	Air Mass Zero I-V Characteristic of Bare Ion Implanted Texturized Surface Cell	32
11	Typical Grain Configuration of Polycrystalline SILSO Wafer	
12	Air Mass Zero I-V Characteristic of Implanted Polycrystalline Wafer Silicon Cell	35
13	Air Mass Zero I-V Characteristic of Pulse Annealed Ion Implanted Cell	38
14	Generalized Rectangular Geometry Unit Cell	40
15	Percent of Total Cell Power Lost by Resistance and Shadowing vs. Line Width for Several Sheet Resistances	43
16	Optimized Front Contact Metallization Pattern for 7.6 cm (3 inch) Cells	45

LIST OF ILLUSTRATIONS (Continued)

<u>NUMBER</u>		<u>PAGE</u>
17	Energy Deposition vs. Depth Profile in Silicon for Electron Beam	49
18	Temperature Profiles in Silicon Following Electron Beam Pulse Anneal	51
19	Helium Ion Backscattering from Furnace and Electron Beam Annealed Implanted Wafers	52
20	Transmission Electron Microscope Photos of Furnace Annealed and Electron Beam Annealed Layers on <100> Silicon	54
21	Measured Arsenic Impurity Profiles for As-Implanted and After Pulse Electron Beam Annealing	55
22	Pulse Anneal Cooling/Recrystallization Sequence	58
23	Regrowth Rates for α -Si to Recrystallize With and Without Single Crystal Substrate	60
24	Diffusion Coefficients for Arsenic and Phosphorus in Solid and Liquid Silicon	61

SECTION I

INTRODUCTION

This is the first quarterly report under a program for "Development of Pulsed Processes for the Manufacture of Solar Cells" being performed under the Automated Production Task of the LSSA Project. Development over the long term is directed toward an extremely abbreviated production scheme for junction solar cells which avoids use of thermal operations and wet chemistry. Immediate emphasis is upon the core element of the production concept: ion implantation. Ion implantation equipment, ion implantation processes and advanced procedures for annealing of ion implantation damage are being addressed.

Under a related previous contract⁽¹⁾ it has been demonstrated that silicon solar cells can be fabricated very rapidly without any furnace treatments, wet chemistry or gas atmosphere operations if ion implantation is employed in conjunction with pulsed energy techniques. Other studies^(2,3,4) have shown 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 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 implanted solar cell structure. To support this effort, the first high throughput dedicated solar cell implanter yet produced is being installed and a next generation implanter is being designed. The machine now becoming operational has throughput capacity equal to approximately 1 MW_e of solar cell product per year and the unit being designed will be able to process close to 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, a particular concept of interest involves application of directed energy pulses of submicrosecond duration to replace thermal operations usually considered necessary to form the solar cell. The most important of these operations for the ion implanted cell is the annealing of radiation damage in the implanted crystal lattice. As part of this program, the pulsed annealing process, which has already been shown to produce the necessary recrystallization effect, is being studied to determine best process parameters and to identify the physical mechanisms involved.

In summary, the major components of this 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 cells.
- (iv) Development and analyses of pulsed energy processes for solar cell fabrication.

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SECTION II

ION IMPLANTATION FACILITIES FOR SOLAR CELL PRODUCTION

2.1 GENERAL CONSIDERATIONS

Ion implantation machines as they presently exist are versatile, sophisticated and expensive. A typical machine, a unit for semiconductor industry production, will provide spectroscopically pure ion beams of most of the elements on the periodic table at any energy from 25 to 200 or more keV. Ion fluences between 10^{11} and 10^{17} ions/cm² are delivered accurately and with virtually complete uniformity and reproducibility. In spite of, and partly because of, their versatility, these implanters are not suitable for solar cell production purposes, not even at 1978 levels. However the limitations are associated with the available machines and not with the process of ion implantation. Correction of implantation machine inadequacies is being addressed in this program.

The general configuration of an ion implanter is suggested by Figure 1. Among the factors which must be considered in the design of ion implantation equipment specifically for solar cells are the following:

- (i) Ion species requirements
- (ii) Ion purity requirements
- (iii) Ion energy requirements

Figure 1. Typical Implanter Configuration

- (iv) Ion fluence requirements
- (v) Fluence uniformity/reproducibility requirements
- (vi) Ion beam/substrate geometry

It can be expected that both N and P-type dopants will be implanted to form a high performance N^+/PP^+ (or P^+/NN^+) silicon solar cell structure. The use of phosphorus and boron ions would be adequate. It is possible that certain advantages may be realized if arsenic is used in place of, or in combination with, phosphorus or if aluminum is substituted for boron. Ions other than P, As, B and Al will not have to be available from ion implanters to be used for silicon solar cells.

In general, as presently performed, ion implantation introduces spectroscopically pure dopant. Before being directed onto the material being processed, the ion beam undergoes mass separation so that only a particular isotope of the desired element is actually implanted. Major simplification of implanter design would result if mass separation were not required. In this case small amounts of contaminant impurities in the beam could not be avoided and would also be implanted. A degree of control might be established over the choice of the major spurious impurity components and if the effect upon performance of the solar cell device could be made benign, implantation without beam analysis might be used in production. Consideration of this possibility in detail is beyond the scope of this program.

The depth to which a dopant is implanted depends upon ion energy. Calculated profiles for representative P^{31+} and As^{75+} implants into silicon are shown in Figures 2 and 3. Actual profiles can extend somewhat deeper because of ion "channeling" effects. Most ion implantation equipment now in use cannot operate or does not operate efficiently at ion energies below roughly 25 keV. Lower energies are desirable for very shallow junction solar cells. If necessary, shallow junctions can be produced even with higher energy ions, for example by implanting through a surface coating, but complications are involved which might be better avoided by selection of implanter design.

Ion fluences for optimized junction and back layer implants in the silicon solar cell depend upon the particular cell structure involved. Fluences between 3×10^{14} and 3×10^{15} ions/cm² are typical for both layers. These levels are much higher than the 10^{12} to 10^{14} ions/cm² fluences which have been used in most semiconductor device applications to date. Until recently implanters for low fluence applications have had low beam currents, a few hundred microamperes maximum or less, and were capable of processing solar cell material only slowly because of beam limitations. Machines with higher currents in the milliamperage range do now exist but in order to achieve good uniformity and to avoid excessive wafer heating at high ion energies these machines have not been designed to utilize the available beam current efficiently.

Figure 2. Phosphorus Ion Profiles in Silicon

Figure 3. Arsenic Ion Profiles in Silicon

Among the major advantages of implantation for applications to devices other than solar cells has been the ability to controllably and reproducibly introduce dopants at very low fluence levels. Much of the design of existing machines has been selected to provide these characteristics. Fluence uniformity over wafers processed and reproducibility from wafer to wafer of better than $\pm 1\%$ are typical of existing equipment but are not necessary for solar cells. Uniformity and reproducibility requirements for solar cells are yet to be established but it is expected that $\pm 10\%$ can be tolerated.

Ion implantation is a directed beam process in which ions are deposited into only those regions which are "seen" by the beam. The high quality surfaces which are characteristic of the materials used in the fabrication of most semiconductor devices can be implanted directly. Usually the material is tilted by a few degrees to misalign the ion beam and the major crystal axis so as to avoid ion channeling through the open structure of the aligned crystal, but problems involving regions of the material surface being shadowed from the beam do not occur. This is not to be the case with solar cell silicon. Low grade surfaces on simply processed wafers or sheets or on as-grown web or ribbon will involve features which will cause shadowing if implantation at a single fixed angle is employed. Texturized surfaces present obvious problems in this respect. Gaps in the doped layers of the cell device cannot be tolerated. Consequently the solar cell material must be implanted so as to avoid any directional shadowing.

Relative alignment of the ion beam and an irregularly featured surface can be varied during the implant. Consideration should also be given to surface shadowing by the mechanism used to hold the material during implant. Fixed holders which involve slotted rails, clips, etc. are to be avoided.

2.2 DEDICATED PROCESS SOLAR CELL IMPLANTER

Figure 4 shows an ion implanter at Spire which was not designed for solar cell purposes and is typical of existing production equipment. Such a machine can deliver ions of most elements on the periodic table at desired energy between 25 and 200 keV. The ion beam is electrostatically scanned to produce uniformity better than $\pm 1.5\%$ over a 3-inch square implant target. Sample to sample reproducibility is better than $\pm 1\%$. Beam current varies with the ion being implanted, the machine shown can deliver up to a maximum of 200 A of P^{31+} and less of most other species. Under normal operation this machine will introduce 10^{15} ion/cm² junctions into roughly (25) 3-inch solar cell wafers per hour. Implanters do exist which deliver higher beam currents, up to a few mA of P^{31+} . However such machines have wafer stations which are batch loaded and incorporate mechanical scanning to achieve tight dose uniformity and to minimize wafer heating at high ion energies. Most of these machines use available ion beam inefficiently, particularly for implants which are not considerably heavier than 10^{15} cm⁻², and throughput for solar cell purposes is not necessarily appreciably greater than that of the implanter which was shown in Figure 4.

Figure 4. Standard, Medium-Current
Production Ion Implanter

In order to put into operation a practical dedicated solar cell process implanter, Spire has worked in conjunction with Varian/Extrion Division to adapt state-of-the-art implanter equipment technology to solar cell production. An implanter of the resulting design has been constructed and installed at Spire. This machine which is shown in Figures 5 and 6 represents successful completion of the first step in development of the massive throughput implantation hardware needed for high volume automated production of silicon solar cells.

Features of the dedicated solar cell process implanter which distinguish it from previously existing machines include:

- (i) High currents of mass analyzed ion beam efficiently utilized on target
- (ii) Low ion energies
- (iii) Ability to rotate the solar cell wafer in the ion beam during implant
- (iv) Elimination of shadowed area resulting from the wafer holding mechanism
- (v) Essentially continuous wafer processing rather than batch loading

Figure 5. Dedicated Solar Cell Process Implanter

Figure 6. Dedicated Solar Cell Process Implanter
Ion Source

The solar cell process implanter has been based upon modifications to existing machine designs. As such this implanter continues to have excessively versatile capabilities. However, included within these capabilities are the ability to operate under conditions considered best suited to solar cell needs. A major objective of the machine design was to provide high currents of necessary ions onto target at low ion energies. Although scheduled operation of the implanter was not initiated during the period of this report, performance objectives were met and exceeded during preliminary testing. Design goal and demonstrated 10 keV ion currents to date are listed below.

Ion	Beam Current on Wafer Target at 10 keV	
	Design Objective	Demonstrated
P ³¹⁺	1.0 mA	4.2 mA
As ⁷⁵⁺	1.0	2.5
B ¹¹⁺	0.7	0.9

The solar cell process implanter has been designed to allow available beam current to be utilized efficiently at the wafer target. Most conventional implanters employ electrostatic and/or mechanical scanning to achieve very uniform fluences over the target region at the expense of considerable loss of beam which never reaches the target substrate. In the solar cell process machine and electromagnetic scanning method is used to "wobble" the beam over the wafer being implanted. Very uniform implants can be achieved by appreciably overscanning the target but the scanner can be operated with small overscan and little beam loss with the sacrifice of some uniformity over the target area. Acceptable uniformities are expected to involve only minor beam losses.

It is anticipated that the implanter will be able to easily maintain beam currents on target in excess of the original design objectives. Wafers are transported individually from standard processing carriers through a vacuum lock into the ion beam then back out through an exit lock and returned to a carrier. Total transport time for each wafer during which the ion beam is not in use is of the order of five seconds. In full operation the machine will perform 10^{15} phosphorus ion/cm² junction implants into better than 300 3-inch wafers per hour or into more than 200 4-inch wafers per hour. Rates for back layer boron implants will be slightly lower. If this implanter were used to capacity on a multiple shift basis it could perform junction or back layer implants into approximately one peak megawatt of solar cell product per year.

Other implanters which have beam currents comparable to those of the solar cell process machine in general have much lower throughput capability because of wafer station design. A high current implanter which might be used for implants at say 200 keV would not be designed to implant individual wafers in a few seconds. At 200 keV, a 10^{15} ion/cm² implant carries sufficient energy to raise the temperature of a 250 μ m thick silicon wafer by approximately 750°C. Aside from problems to be encountered in trying to anneal the type of radiation damage which would remain after implant, transport and handling of high temperature wafers would be impractical. Processing in which many wafers are implanted over a relatively long period of time is the usually accepted approach and, as a result, high current machine designs involve batch loading. However the solar cell process implanter is planned for low ion energies. At 10 keV, a 10^{15} ion/cm² implant could raise temperature of a 250 μ m thick wafer by only 37°C.

A unique feature of the implanter which has been provided to satisfy solar cell processing needs is a wafer holding mechanism which spins the wafer at one revolution per second in the ion beam during implant. The mechanism is illustrated in Figure 7. Wafer rotation in combination with off-axis tilt is an important function for a number of reasons, the most important of which are:

- (i) The total forward surface of the wafer is implanted without any void regions due to the holding mechanism.

Figure 7. Wafer Rotation/Holder for
Solar Cell Implants

- (ii) Silicon material with irregular surface features, texturized surface, etc. is multi-directionally implanted so that implanted layers without gaps due to shadowing are produced.
- (iii) Circumferential uniformity over the implanted wafer is assured regardless of any lack of symmetry in the ion beam itself.

In support of the program of this report the solar cell process implanter will be utilized for a number of functions including:

- (i) Advancement of cell performance status.
- (ii) Assessment of technical demands on ion specie, energy, dose, uniformity, etc.
- (iii) Investigation of special annealing requirements associated with very high rate implants.
- (iv) Investigation of implant requirements for polycrystalline materials, texturized surfaces and special structures or materials.
- (v) Evaluation of process reliability, economics, energy utilization, etc.

2.3 DESIGN OF AUTOMATED PRODUCTION IMPLANTER

The implanter described above can serve immediate needs for implanted solar cell process and production development. But if implantation is to be practical for use as the core of automated production facilities to meet objectives for the mid-1980's, dedicated solar cell implanters must be developed which have much higher beam currents and different operational characteristics. Under this program Spire is performing the basic engineering design of a solar cell production implanter which will operate continuously at a delivered beam current level of not less than 100 milliamperes. Solar cell product throughput of one such machine in full operation is to be approximately 100 MW_e peak output. In order to conduct this design study Spire has employed Peter H. Rose, who is generally recognized as the world authority on ion implanter design and construction.

A set of Functional Requirements has been defined to represent the minimum performance objectives to met by the automated production implanter being designed. These Functional Requirements are summarized in Table I. The implanter must provide continuous, uniform, reproducible, high volume throughput. The design being developed is to be conservative with high assurance of meeting all objectives. The components being considered are identified in Figure 8.

An extremely important assumption is involved in this design study: the machine will incorporate mass separation

Table I

Functional Requirements
Automated Production Implanter

Ion Species:	p31+, As75+, B11+, (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 p31+
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 routine and predictable component fail- ure maintenance

Figure 8. Components of Automated Production Implanter

in the ion beam to maintain isotopic purity characteristic of present generation implanters. The possibility does exist that high quality ion sources could be employed directly for solar cells without the use of mass separation to remove unavoidable low level contaminant impurities. However, until the solar cell silicon material to be used in volume production has been specified and thoroughly characterized for possible spurious contaminant effects, it cannot be validly assumed that totally pure ion beams will not be required. High current ion beams without mass ion separation are within the limits of available technology already demonstrated. The purpose of this study is to insure that adequate beams with mass separation can also be available.

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SECTION III

SOLAR CELL STUDIES

3.1 OBJECTIVES

Developmental efforts related to ion implanted solar cells have usually been directed toward demonstration of specific processing approaches based around implantation. Emphasis has generally been upon the use of implantation rather than upon optimization of solar cell structure and performance. Optimization work corresponding to that which has been performed on diffused junction solar cells has not been conducted on implanted junction devices. An assumed essential equivalence of implantation and diffusion so far as solar cell technical performance is concerned has not been experimentally confirmed.

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

- (i) Improvement of the structure and performance of cells fabricated using implantation for dopant introduction.
- (ii) Assessment of relative performance of otherwise identical cells with diffused and ion implanted junctions.

- (iii) Integration of high performance cell structural features into abbreviated implantation/pulsed energy processing being developed for low cost automated production.

3.2 IMPLANTED CELL PERFORMANCE STATUS

During the period of this report, solar cell efforts were primarily preparatory. Developmental emphasis is to be upon 3-inch diameter single crystal wafer cells and upon 5 x 5 cm or larger cells from cast polycrystalline sheet. Required processing fixtures and masks for these configurations were planned but not completed during the reporting period. However some initial tests were performed using 2 x 2 cm masks and fixtures on hand. The results of these tests are discussed below.

3.2.1 Planar Surface Cells

During preliminary trial operation of the solar cell process implanter described in Section 2.2, a number of test wafers were implanted. In order to demonstrate that cells with acceptable performance characteristics would be produced by the implanter, a few of the test wafers were fabricated into 2 x 2 cm cells using the process described in Table II. Cell efficiencies in the test group of 10 cells ranged between 11.9 and 12.4% Air Mass Zero. The AMO I-V characteristic of one cell is shown in Figure 9. An approximate Air Mass One characteristic for the same cell was determined by measuring actual cell I_{SC} outside on a clear day, correcting to an approximate $(I_{SC})_{AMI}$ by reference to a terrestrial standard cell supplied by NASA Lewis Research Center, then forcing output of the cell under a simulator to this I_{SC} value. Estimated efficiency of the cell shown was 14.8% AMI.

Table II
Implanted N⁺/PP⁺ Cell Process Outline

Starting Material:	1 ohm-cm (111) or (100) Si
	Front Surface: Polished
	Back Surface : Bright Etched
Process:	Phosphorus implant front
	Boron implant back
	Furnace anneal
	Evaporate front contact base
	Photoprocess contact configuration
	Plate front contact
	Sinter
	Evaporate back contact
	Evaporate AR coating

Figure 9. Air Mass Zero I-V Characteristic of Test Cell
From Solar Cell Process Implanter

A number of improvements remain to be made in the structure of the basic implanted cell which will increase efficiencies beyond those described above. In particular, the cells described had nonoptimized dopant profiles, somewhat high junction doping levels, overly deep $0.25\text{ }\mu\text{m}$ junction depth due to ion channeling effects and noneffective internal reflection of long wavelength photons at the back contact.

3.2.2 Texturized Surface Cells

Because ion implantation is a directionally dependent process in which spatial orientation of the ion beam and the surface being implanted has importance, texturized surfaces require certain variations of basic implantation procedure. The solar cell process implanter incorporates the ability to rotate a wafer being implanted in the ion beam so that directional symmetry can be preserved even though the wafer axis is tilted relative to the beam axis to minimize primary channeling effects. Experimental work on texturized surfaces has not yet been initiated on this machine. However, preliminary tests on a standard implanter confirm that texturized surfaces do not present major problems.

Figure 10 shows the Air Mass Zero I-V characteristic of a texturized surface silicon cell fabricated using essentially the same process as was listed in Table II. To satisfactorily implant the texturized surface in a standard implantation machine, the junction implant was performed in four steps. One quarter of the total implant fluence was introduced with the ion beam identically aligned relative to each of the pyramidal face orientations on the wafer

Figure 10. Air Mass Zero I-V Characteristic of Bare Ion Implanted Texturized Surface Cell

surface. Parameters for performance better than the 10.8% AMO exhibited by the bare cell in Figure 10 can now be defined and will be utilized in tests to be conducted using the solar cell process implanter.

3.2.3 Cast Polycrystalline Sheet Cells

Non-single crystal silicon materials also present no particular problems for implantation. Considerations of grain boundary diffusion effects, preferential dopant collection in boundary regions, etc. can probably be ignored for properly conducted implantation and implant damage annealing procedures. As part of this program, processes will be optimized for fabricating ion implanted cells from cast polycrystalline sheet silicon. The material to be used is "SILSO" silicon available in 10 x 10 cm sheets from Wacker-Chemitronic. Figure 11 illustrates typical grain configuration of this product.

Preliminary tests have been conducted using the polycrystalline sheet material and an elementary cell process. A routine 25 keV $3 \times 10^{15} \text{ cm}^{-2}$ phosphorus ion implant on a standard implanter was employed. Figure 12 illustrates the AMO I-V characteristic of a typical cell. Equivalent processing of single crystal wafer material would have resulted in somewhat higher short circuit current levels due to better long wavelength response characteristics.

Figure 11. Typical Grain Configuration of Polycrystalline SILSO Wafer

Figure 12. Air Mass Zero I-V Characteristic of Implanted Polycrystalline Wafer Silicon Cell

3.2.4 Pulse Annealed Cells

A total cell production approach being developed by Spire toward use in automated production machines involves ion implantation in conjunction with directed energy pulse methods which replace all thermal operations. The result is high speed, room temperature processing conducted in a vacuum environment common to all steps. Feasibility has been previously demonstrated(1).

The most important and demanding pulsed energy process steps are those used to anneal radiation damage to the silicon lattice caused by the ion implants. Investigations related to pulsed energy processes under the present program are to emphasize development of parameters for implant damage annealing and identification of the mechanisms associated with these submicrosecond processing effects. Mechanism studies are discussed in Section 4.2.

Annealing of implantation damage is an essential step in the fabrication of an ion implanted solar cell. Experimental work on development of optimized pulsed electron beam parameters for annealing of solar cell junction implants is in progress. The facility being employed generates an almost uniform beam spot a little more than two inches in diameter. Parameters of the beam used for silicon solar cell junction annealing are as follows:

Pulse duration:	10^{-7} second
Mean electron energy:	20 keV
Beam fluence:	0.1-0.3 cal/cm ²

A few sample wafers from pulse annealing tests have been fabricated into 2 x 2 cm cells. Figure 13 shows the AMO I-V characteristic of a typical cell. Efficiencies of pulse annealed cells now approach 12% AMO. Because of factors to be discussed in Section IV, considerably better performance is expected to be achieved during coming months.

3.3 CONTACT DESIGN

Ion implantation provides exacting control over total dopant density in the junction layer. Optimization of cell performance is expected to rely in some part upon selection of a dopant level which does not cause dead layer effects. Unless a very effective front contact structure is employed, this selection could be compromised by a need to reduce junction layer sheet resistance in order to limit series resistance losses. For this reason, analytical studies related to front contact configurations have been carried out as part of the implanted solar cell development effort. The purpose of these studies has been twofold: to optimize existing contact patterns for use with high efficiency ion implanted cells, and to design new contact patterns with improved performance. The result of these studies has been the design of a new contact pattern expected to be used on the three inch diameter ion implanted cells of this program. The basic analytic approach and grid design selected are discussed below.

Front contact dependant losses of cell power output can be assumed to result from four sources:

- (i) Shadowing of cell area by metal

Figure 13. Air Mass Zero I-V Characteristic of Pulse Annealed Ion Implanted Cell

- (ii) Resistive losses in fingers and busses
- (iii) Sheet resistance losses on the silicon front surface implanted layer
- (iv) Contact resistance

For simplicity, the cross section of a contact grid line is assumed to be ohmic. Most contact patterns can be analyzed by conceptually breaking them down into many simple geometries, and summing the losses from each of these units to find the loss for the whole cell⁽⁵⁾. The simplest such geometry, the rectangular unit, is shown in Figure 14. Other simple units may be triangular, trapezoidal, etc.

For analysis, power loss due to resistance is taken to be I^2R , integrated over the appropriate area^(5,7). For example, in the case of the rectangular unit:

$$P_r = \text{Power loss due to resistance in finger}$$

$$= \int I^2 dR$$

$$dR = \rho_m \frac{dx}{WIT}$$

so

$$P_r = \frac{I_o^2 \rho_m D^2 L^3}{3 WIT}$$

$$P_o = \text{Power loss due to sheet resistance}$$

$$= \int_A I^2 dR$$

Figure 14. Generalized Rectangular Geometry Unit Cell.

$$dR = R_{sh} \frac{dY}{dX}$$

$dI = I_o y' dx$ (current assumed to flow perpendicular to contact)

$$P_o = 1/3 R_{sh} I_o^2 D^3 L$$

$$\begin{aligned} P_c &= \text{Power loss due to contact resistance} \\ &= \frac{I_o^2 R_c D^2 L}{W} \end{aligned}$$

To find losses as a fraction of total possible power from this area, it is necessary to divide by the total power $I_o V L D$. To this must be added the fractional loss due to shadowing,

$$\bar{P}_s = \text{Fractional loss due to shadowing} = \frac{W}{D}$$

To find the total fractional power loss

$$\bar{P}_T = \frac{I_o D L^2 \rho_m}{3 W T V} + \frac{R_{sh} I_o D^2}{3 V} + \frac{I_o R_c D}{W V} + \frac{W}{D}$$

here: ρ_m = metallization resistivity in Ω -cm
 R_{sh} = implanted layer sheet resistivity in Ω /square
 R_c = contact resistance in Ω -cm² (assumed ohmic)
 V = operating voltage
 I_o = operating current production density in amps/cm²
 T = metallization thickness.

Several linearizing assumptions are made regarding independence of operating point on grid pattern. As long as power loss in the contact is low, which is true for any case likely to be considered, this will not effect the results. It is possible to reduce metal to silicon contact resistance to low levels by proper choice of contact metals and sintering cycle and contact resistance has been assumed to be negligible for grid configuration analysis.

Note that if the finger half-width W and spacing D could both be decreased while metal thickness T_n is held constant, the total losses would uniformly decrease. This implies that metallization fingers should be designed as thin as the appropriate technology allows. In fact, since metal thickness cannot be much larger than line width, extremely thin lines are not practical. As indicated in Figure 15, this constraint added, lines of width less than about 15 microns prove to lose efficiency. The initial cell grid pattern selected is based on a total line width of 35 microns.

Since loss is also directly dependent on line length L , loss can be minimized by lowering L . This is done by increasing the number of output terminals. The advantage of adding output terminals levels out at around 3 to 4 terminals. Four terminals have been selected for further designs.

A computer program was written to calculate the power losses of various metallization patterns using the approach

Figure 15. Percent of Total Cell Power Lost by Resistance and Shadowing vs. Line Width for Several Sheet Resistances

outlined above. Finger spacings were optimized while other parameters were held constant. This program was used both to design optimum grid patterns, and to graph the effects of variations in cell process parameters (line width, sheet resistivity, etc) as an aid in cell design.

Several different grid patterns were analyzed for this study. In order to take maximum advantage of very narrow line widths, patterns were designed specifically to reduce the distance travelled along the line to an output terminal. This permits extremely narrow lines to be used without excess loss due to resistance. Figure 16 shows the Spire "Starburst" contact pattern selected for use on 3-inch diameter implanted cells. Total power losses by the contact grid (shadow and resistive) are predicted to be slightly less than five percent.

SPIRE No. 10052-2
"STARBURST"

Figure 16. Optimized Front Contact Metallization
Pattern for 7.6 cm (3 inch) Cells

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SECTION IV

PULSED ENERGY PROCESSING STUDIES

4.1 GENERAL

Ion implantation could be utilized in a number of solar cell production process variations. One approach with considerable potential for becoming extremely effective for automated production at high volume levels involves the combination of ion implantation and pulsed energy processing techniques.

Pulsed energy, deposited into the region being processed by an electron beam, a laser or some other directed energy source, can replace the thermal operations normally considered necessary in the fabrication of a junction solar cell. Directly or indirectly, elevated temperature steps are responsible for most of the energy consumption, waste generation, process complexity and time required to produce a silicon solar cell from adequate starting material. Each thermal step has the purpose of performing some treatment, annealing, sintering, etc., in the vicinity of the device surface. Very short duration pulses of directed energy can cause equivalent process effects to occur. Major process simplifications and cost reductions are expected as a result.

Pulsed processing has been under development as a replacement for furnace operations normally used in solar

cell fabrication. However it is found that pulsed energy techniques produce somewhat different results which in many instances are technically superior to those produced by a furnace process. This appears to be the case for annealing of ion implantation damage, a key process in fabrication of an implanted cell and the subject of the pulsed energy process studies under this program.

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. Spire has investigated the use of several types of lasers, high intensity flash lamps and pulsed electron beams. Because of considerations related to obtaining sufficient energy deposition, uniformity and reproducibility over reasonably large areas with ability to build efficient high repetition rate production machines, Spire is emphasizing use of the pulsed electron beam.

The electron beam being used for experimental annealing of ion implantation damage has duration of 10^{-7} second. Mean electron energy is under 20 keV. The experimental facility produces a 2-inch diameter uniform beam. Energy deposition profile in silicon is approximately as shown in Figure 17. Almost all of the energy carried by the beam is deposited into the first 2 m of the surface being processed. The electron pulse is so short that thermal conduction from the deposition region during the pulse is negligible and very high temperatures can be achieved in this

Figure 17. Energy Deposition vs. Depth Profile in Silicon for Electron Beam

region by very modest input energy. Figure 18 shows predicted temperature profiles in the silicon at the end of the electron pulse and at a few instants thereafter. Although the electron beam carries only 0.2 cal/cm^2 to the silicon, the silicon surface region momentarily reaches melting temperature. The thermal spike relaxes after the pulse by conduction.

It has been found that implanted layers exhibit better structural quality after pulsed electron beam annealing than after furnace annealing. Structural evaluations of importance to this program are being performed by S. S. Lau, W. Tseng and J. Mayer of California Institute of Technology. Some data has been presented elsewhere; Figure 19 shows helium ion backscattering measurement results obtained on identical implanted samples without any annealing, with furnace annealing and with pulsed electron beam annealing. The sample which was not annealed exhibits surface region backscattering characteristic of amorphous material. The furnace annealed sample shows backscattering typical of good conventional annealing procedure. The backscattering has been much reduced by crystalline regrowth of the implanted layer but not eliminated because of the formation of polycrystallites within the layer. The sample annealed with the pulsed electron beam exhibits very low backscattering comparable to that produced by virgin single crystal silicon. The pulse annealed layer has been recrystallized to single crystal condition.

Figure 18. Temperature Profiles in Silicon Following Electron Beam Pulse Anneal

FIGURE 19. Helium Ion Backscattering from Furnace and Electron Beam Annealed Implanted Wafers.

Transmission electron microscopy studies have also been conducted upon furnace and pulsed electron beam annealed implanted layers. Typical results are shown in Figure 20. Under TEM examination, the furnace annealed layers show dislocation loops and residual disorder effects characteristic of conventional annealing practice. However, the layers annealed with the pulsed electron beam exhibit virtually total absence of dislocations or any other mechanical defects.

Pulsed annealing is found to produce more complete electrical activation of the implanted dopant. Redistribution of impurities as a result of pulsing is found to occur. Figure 21 shows a typical result measured using helium ion backscattering methods. The figure shows the as-implanted profile of a heavy 25 keV arsenic implant and the profile of the same implant after pulsed electron beam anneal. The arsenic atoms have moved appreciably deeper into the silicon and the profile peak below the surface has been eliminated. Correct utilization of these effects is to be an important factor in the development of high efficiency pulse processed cells.

4.2 MECHANISM OF THE PULSE ANNEAL PROCESS

Spire has been utilizing pulsed electron beams and lasers for annealing of ion implantation damage since early 1974. Development as a potential production processing technique has been hampered because the interrelated phenomena occurring are complex and the mechanism or mechanisms involved in the high speed transient annealing have not been known. As part of this program, investigation has been in progress to attempt to identify the primary factors associated with the pulse annealing mechanism.

A. Thermally Annealed Implanted Layer

B. Pulsed Electron Beam Annealed Implanted Layer

Figure 20. Transmission Electron Microscope Photos of Furnace Annealed and Electron Beam Annealed Layers on $\langle 100 \rangle$ Silicon. Implants: 10 keV p^{31+} 10^{15} cm^{-2} .

Figure 21. Measured Arsenic Impurity Profiles for As-Implanted and After Pulse Electron Beam Annealing

The structural perfection exhibited by implanted layers after pulse annealing indicates that the damaged layer recrystallizes epitaxially on the undamaged substrate during the anneal. The underlying silicon crystal lattice serves as the nucleation surface for recrystallization which takes place directionally from the undamaged region to the surface. Explanation is required of how this regrowth is able to take place so flawlessly as a result of a single energy pulse lasting less than a microsecond.

A number of factors are involved in the pulse anneal mechanism including:

- (i) Spatial distribution of the deposited energy.
- (ii) Resulting maximum temperature distribution and temperature gradient at the profile edge.
- (iii) Manner in which heat can be lost from the surface layer.

A complete quantitative explanation which is not necessary for this program may also have to consider certain other factors including:

(iv) Effects of ionization

(v) Relative character of amorphous and crystalline silicon.

Calculations of temperature profiles produced in silicon material by the implant anneal electron beam pulse employed experimentally show that the implanted layer reaches melting temperature. However insufficient additional energy is introduced to allow complete melting of the region to occur and additional temperature rise to take place. A representative maximum temperature profile was shown in Figure 18. The surface layer at melting temperature might be considered to be in a glassy amorphous condition. At some point below the surface a steep temperature gradient exists between this material and single crystal silicon of the substrate.

During time frames of the order of microseconds, appreciable heat losses from the silicon layer at melting temperature can take place only by conduction into the crystalline material below. No temperature gradient exists across the layer at melting temperature and consequently heat is effectively trapped within this layer. Only the material at the temperature gradient interface is able to undergo cooling. Consequently epitaxial regrowth takes place at this interface, energy is given up at the interface and the crystal front progresses monotonically toward the surface. Because of the absence of a temperature gradient within the noncrystallized region at melting temperature, cooling can occur only as the crystal structure grows. The cooling sequence is suggested in Figure 22.

Figure 22. Pulse Anneal Cooling/Recrystallization Sequence

If the time frames involved in the recrystallization process were to be appreciably greater than tens of microseconds, the only significant heat loss mechanism available to the surface layer would no longer be conduction into the crystalline material below. Figure 23 shows Arrhenius plots of experimentally measured regrowth rates of silicon as a function of temperature^(8,9). When these plots are extrapolated to the melting temperature of silicon it can be seen that a growth rate exceeding 10^8 Å/sec is predicted. Consequently the implanted layer which is of the order of 10^3 Å thick can be expected to recrystallize in a period of microseconds.

The dopant redistribution effect shown in Figure 21 must also be explained. If it is assumed that the redistribution indicated takes place in approximately 10^{-6} seconds, then it can be calculated that effective diffusion coefficient of the arsenic impurity atoms must be roughly 10^{-5} cm²/cm during the process. Existing information^(10,11) regarding abrupt changes in diffusion coefficient which take place between the solid and liquid phases of silicon at melting temperature indicate a value of the order of 10^{-5} cm²/sec can be expected. Known diffusion coefficient values for phosphorus and arsenic are shown in Figure 24.

Figure 23. Regrowth Rates for α -Si to Recrystallize With and Without Single Crystal Substrate

Figure 24. Diffusion Coefficients for Arsenic and Phosphorus in Solid and Liquid Silicon

All redistribution results with pulsed annealing are consistent with diffusion coefficients between the solid and liquid values at melting temperature. This is in agreement with the annealing mechanism now believed to be involved.

SECTION V

CONCLUSIONS

This report has described the initial months of a new program involving ion implantation and processing of ion implanted cells. Status of the program is advanced. Important results reported at this time include:

- (i) A dedicated solar cell process ion implanter is now operational. This machine can implant solar cell N^+ and P^+ layers into several hundred 3 or 4 inch wafers per hour.
- (ii) Functional requirements have been defined for an automated production implanter capable of processing roughly 100 MW_e of solar cell product per year. Design of the machine is in progress.
- (iii) Processing for ion implanted solar cells is being developed. Ion implanted cells with efficiencies of approximately 12.5% AMO (15% AM1) are now being achieved. Introduction of new contact designs and improved processes is expected to result in rapid improvement to higher performance values.

- (iv) Pulsed energy processing for implant damage annealing is being investigated. Pulse annealed implanted layers have been shown to have certain technically superior characteristics relative to best furnace annealed layers.
- (v) A mechanism which can explain pulsed energy transient processing has been identified and is described.

SECTION VI
NEW TECHNOLOGY

No new technology has been developed to completion for this quarterly report.

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