DOE/JPL/956797-02
(DE85002508)

EXCIMER LASER ANNEALING TO FABRICATE LOW COST SOLAR CELLS

Quarterly Technical Report No. 2 for the Period Covering
July 1—September 30, 1984

By
Anton C. Greenwald

October 1984

Work Performed Under Contract No. NAS-7-100-956797

Spire Corporation
Bedford, Massachusetts

Technical Information Center
Office of Scientific and Technical Information
United States Department of Energy

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

This report has been reproduced directly from the best available copy.

Available from the National Technical Information Service, U. S. Department of Commerce, Springfield, Virginia 22161.

Price: Printed Copy A03
Microfiche A01

Codes are used for pricing all publications. The code is determined by the number of pages in the publication. Information pertaining to the pricing codes can be found in the current issues of the following publications, which are generally available in most libraries: *Energy Research Abstracts (ERA); Government Reports Announcements* and Index *(GRA* and I); *Scientific and Technical Abstract Reports (STAR);* and publication NTIS-PR-360 available from NTIS at the above address.

DOE/JPL/956797-02
(DE85002508)
Distribution Category UC-63b

EXCIMER LASER ANNEALING TO FABRICATE LOW COST SOLAR CELLS

Quarterly Technical Report No. 2
For Period Covering 1 July to 30 September 1984

Contract No. 956797

Jet Propulsion Laboratory
Flat-Plate Solar Array Project
Module Performance and Failure Analysis Area

Approved by: Anton Greenwald
Anton C. Greenwald, Principal Investigator

Approved by: Mark B. Spitzer
Mark B. Spitzer, Program Manager

SPIRE CORPORATION
Patriots Park
Bedford, Massachusetts 01730

TABLE OF CONTENTS

Section		Page
1	INTRODUCTION	1-1
2	TECHNICAL PROGRESS	2-1
	2.1 Task (1)(A): Select Process	2-1
	2.2 Task (1)(B): Assess Effect of Process Variables	2-1
	2.2.1 Optical Equipment	2-2
	2.2.2 Optimization of Front Junction Parameters	2-9
	2.2.3 Optimizing Parameters for Screen Printed Contacts	2-20
	2.2.4 Optimizing BSF Parameters	2-20
	2.3 Task (1)(C): Demonstrate Appropriateness of Source	2-21
3	CONCLUSIONS AND RECOMMENDATIONS	3-1
4	PLANNED WORK IN THE NEXT REPORTING PERIOD	4-1

LIST OF ILLUSTRATIONS

Number		Page
1	Experimental Laser Annealing Station	2-3
2	Pulsed Excimer Laser Beam Intensity Versus Horizontal Distance At Output Lens	2-5
3a	Burn Pattern from Excimer Laser at Focusing Lens	2-6
3b	Burn Pattern from Excimer Laser at Sample Position	2-6
4	Fluence Measured Across Beam Length Horizontally at Lens	2-7
5	Fluence Measured Across Beam Width Vertically at Lens	2-8
6	Maximum Laser Line Width at Sample as a Function of Lens Position	2-10
7	Sheet Resistance Uniformity of PELA Sample 4520-1	2-13
8	PELA Junction Depth Profile Sample 4520-1	2-14
9	Reflectance from 2x2 cm Cells, No AR Coating	2-19
10	Scanning Pattern for Annealing a 100 cm^2 Square Wafer	2-22
11	Program Schedule	4-2

LIST OF TABLES

Number		Page
1	Ion Implantation Parameters	2-1
2	Selected Cell Results from First PELA Experiment with AR Coating	2-12
3	Cell Results from Second Experiment (No AR Coating)	2-16
4	Cell Results from Third Experiment (No AR Coating)	2-17
5	Experiment Four - Comparison of PELA at 248 nm and 308 nm Light	2-20

ABSTRACT

The objective of this research is to determine whether or not pulsed excimer laser annealing (PELA) of ion-implanted junctions is a cost effective replacment for diffused junctions in the fabrication of crystalline silicon solar cells. The preliminary economic analysis completed during the first quarter of this program showed that the use of ion implantation and PELA to fabricate both the front junction and back surface field (BSF) would cost approximately 35¢ per peak watt (Wp), compared to a cost of 15¢/Wp for a hypothetical baseline diffusion process that it is assumed to yield cells with an average efficiency of 14%. A cost advantage may be attained, however, if the implant-PELA process yields an improvement in the average cell efficiency from 14% to 16%; this improvement would lower the overall cost of the module by about 15¢/Wp.

The technical goal of this research is to develop an optimized PELA process compatible with commercial production, and to demonstrate increased cell efficiency with sufficient product for adequate statistical analysis. During the second quarter of this program, it was shown that the laser chosen for this work, operating with an output power of 50 watts, demonstrated sufficient processing speed for commercial production. Also during this time period, the PELA process was optimized for annealing phosphorus implants in polished p-type silicon wafers. The best solar cell obtained in this way had an efficiency of 10.5% at AM1 illumination without AR coating. This efficiency is equal to that of co-processed furnace annealed ion-implanted controls.

Work planned during the next quarter includes optimization of the PELA process parameters for use with screen printed contacts, optimization of the PELA process for use with texture-etched material, and development of a set of parameters to anneal boron or boron-triflouride implants.

SECTION 1
INTRODUCTION

The objective of this research is to show whether or not pulsed excimer laser annealing (PELA) of ion implanted junctions is a cost effective replacement for diffused junctions in fabricating silicon solar cells. Required experiments and analysis are described below.

The first task (1A) is to select a process group which has functional equivalence to the baseline process group defined by JPL. Ion implantation and laser annealing have been used in place of diffusion of phosphorus for the front junction, and in place of aluminum drive-in for the back surface field.

The second task (1B) is to assess the sensitivity of the selected process to all significant input variables. The following parameters are being varied in this study: wavelength, beam uniformity, fluence, overlap, focusing optics, surface preparation, and ion implant species. Other parameters (for example, pulse width, ion implant energy and dose) are in this work fixed, and are based on past published work. Further development of PELA is also in progress to show the compatibility of this process with commercial screen printed contact formation processes. Included in this task is the development of annealing of texture-etched surfaces.

The third task (1C) is to show the suitability of the specific excimer laser selected for this application. The KrF laser used in this work has an output power of 50 watts. This laser can anneal an area of 25 cm^2 per second, which is sufficient for the commercial application envisioned. The laser has been demonstrated and this task is complete.

The fourth task (1D) is to demonstrate the achievement of a process cost reduction by producing a quantity of cells utilizing the proposed process group. The planned demonstration will comprise fabrication of 300 solar cells 100 mm in diameter, plus controls, using the equipment identified for production use, although full automation will not be used. The average cell efficiency and yield of this demonstration will be used in calculating the cost of this process.

The fifth task (3A) is to perform a preliminary economic analysis of the selected laser process compared with competing technologies. The results, detailed in the first quarterly report for this contract, indicate that ion implantation and PELA of both front and back surfaces of a wafer would cost about twice as much as the equivalent baseline process group. However, since the PELA process is expected to result in more efficient cells, significant cost savings can still be realized. If the technical results of this program show that the back implant and anneal are not needed, then the cost savings would be almost $0.32/peak watt.

The sixth task (3B) is a final economic analysis of this process using the yield and efficiency data of the demonstration experiment (Task 1C). This experiment will include furnace annealed controls, and an economic comparison between PELA and furnace annealing will be made.

SECTION 2

TECHNICAL PROGRESS

2.1 TASK (1)(A): SELECT PROCESS

The process chosen for the application of excimer lasers to the fabrication of silicon solar cells consists of non-mass analyzed (NMA) ion implantation of (a) phosphorus for the front junction and (b) boron-triflouride for the back surface field (BSF) followed by (c) pulsed excimer laser annealing (PELA) of both sides. This PELA process replaces the following steps in the baseline process outlined by JPL: diffusion of the junction, application of aluminum and drive-in to form the back surface field, and finally a cleaning step. Detailed justification of this choice was presented in the first quarterly technical report for this contract.

2.2 TASK (1)(B): ASSESS EFFECT OF PROCESS VARIABLES

The objective of this task is to determine the sensitivity of the selected process, PELA of ion implanted junctions, to all significant process parameters. These parameters include laser wavelength, pulse width, beam uniformity, fluence and percentage overlap as well as sample surface preparation, implanted ion type, ion dose, ion energy, sample temperature and atmosphere. Previous experimental results imply that the following parameters should be fixed: ion implant energy and dose (see Table 1), and laser pulse width.[1] For ease of processing, the sample will be pulsed at room temperature in atmosphere.[2]

TABLE 1. ION IMPLANTATION PARAMETERS

Surface Condition	Polished or Bright-Etched	Texture-Etched
Front Junction	$^{31}P^+$, 10 keV $2.5 \times 10^{15}/cm^2$	$^{31}P^+$, 10 keV $4.3 \times 10^{15}/cm^2$
Back Surface Field	$^{11}B^+$, or BF_2^+ 25 keV $2.5 \times 10^{15}/cm^2$	$^{11}B^+$, or BF_2^+ 25 keV $5 \times 10^{15}/cm^2$

This study primarily addresses the effect of the laser wavelength, fluence, and overlap on polished and texture-etched wafers, with phosphorus or boron implants. The work was broken up into five subtasks:

(1) Setting up the optical equipment

(2) Optimizing parameters to anneal phosphorus implants in polished surfaces (front junction).

(3) Optimizing parameters to anneal phosphorus implants in texture-etched surfaces.

(4) Optimizing parameters for screen printed contacts.

(5) Optimizing parameters for fabricating the back surface field (BSF).

The goal of each subtask and the work accomplished during the second quarter of this contract is summarized below.

2.2.1 Optical Equipment

The laser, mirror, focusing lens, and scanning table are set up as shown in Figure 1. The pulsed excimer laser is either a model 2200 or 2400 manufactured by Questek, Inc. of Bedford, MA. Different lasers, during final production testing, were made available to this program on a service basis. The x-y translation table has a linear accuracy of 0.0005 in./in. of travel, a positional repeatability of 0.002 in., and a maximum travel of 5 inches in either direction. The stepping motor and controller are set for 0.001 inch per step with a maximum speed of 10 inches (10,000 steps) per second and maximum acceleration/deceleration of 250,000 steps/second/second. The controller is programmable and can trigger the laser after each step or, in a high speed scan, turn the laser on or off before a long continuous scan. In the latter case synchronization depends upon the repetition rate of the independant laser control and the speed of the moving table. The mirror shown in Figure 1 is a front surface aluminum coated mirror with an antireflection coating for 278 nm at 45 degrees incidence angle. The cylindrical lens is synthetic quartz of uv grade material, plano-convex with flat side up, an antireflection coating on both sides for 278 nm, and a focal length of 250 mm. Minor damage to the AR coating is observed at 248 nm irradiation at 0.1 J/cm^2. The vendor would not identify the material.

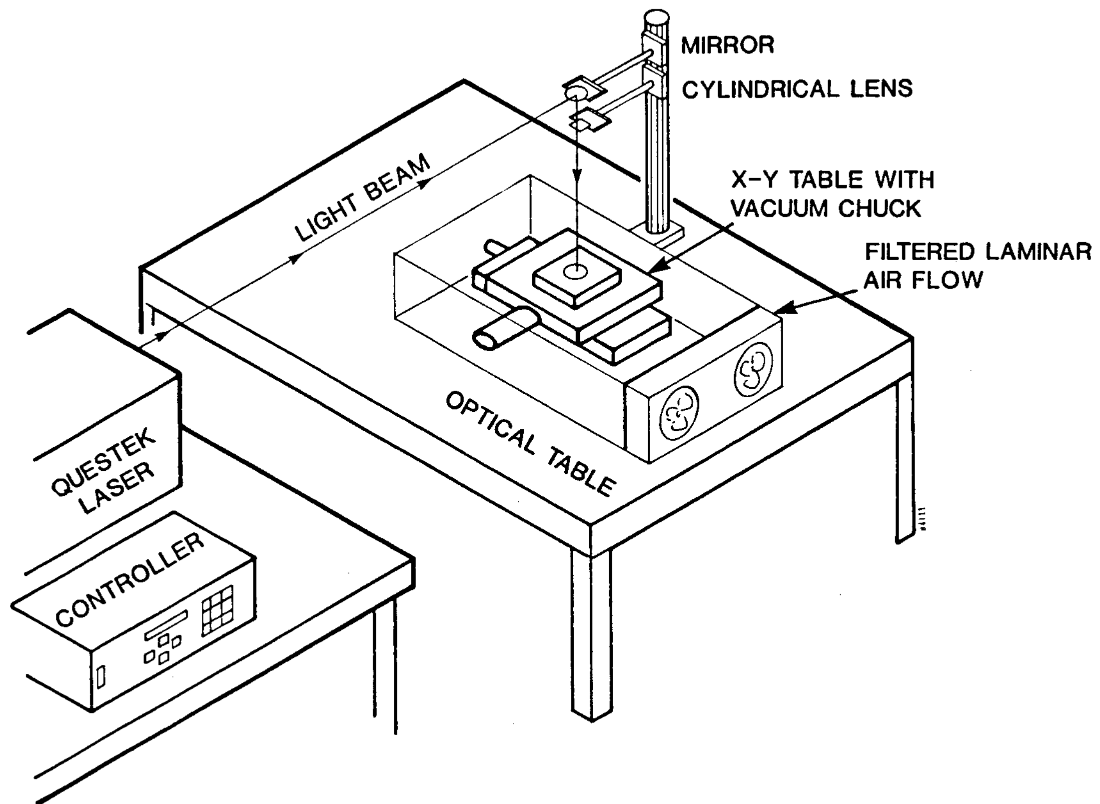

FIGURE 1. EXPERIMENTAL LASER ANNEALING STATION.

The excimer laser can be operated in either of two configurations; as a stable or unstable resonator. In the first case the output window and rear mirror of the laser are planar and aligned parallel within very close tolerance. This configuration has the highest output power; the final adjustment of the laser optics is made by maximizing the output power. The unstable resonator configuration (with large radius concave surfaces on the optics) has 15 to 20% lower output power; however, this beam can be focused to a smaller width. Because the eventual processing cost is related to output power which had to be maximized (Section 2.3), and because a focal line width of about 1 mm was desired, all experiments to date used the stable resonator configuration of the laser.

Typical uniformity of the stable resonator configuration is $\pm 2\%$. This value is determined from data in Figure 2, which shows the beam intensity meaured along a horizontal line near the laser exit window by a multisegment pyrometer. The two-dimensional beam pattern can be visualized using thermal sensitive paper, which bleaches with increased beam intensity in a non-linear fashion. The pattern seen at the laser exit window diverges along the path (approximately 75 cm long) to the focusing lens (Figure 3a). The pattern is not visable when focused at the sample position (Figure 3b). Non-uniformities of $\pm 5\%$ are visable in annealing patterns on texture-etched material, but not on polished wafers.

The beam intensity transmitted through the focusing lens is measured by a large area power meter placed just below the lens. The total intensity measured at this point is 0.80 of the intensity measured at the laser for both 308 and 248 nm light. This loss of intensity is not fully accounted for at this time. Both mirror and lens are supposed to be of the finest optical quality with appropriate antireflection coatings. Some energy is lost due to beam divergence, some lost to absorption air, and flourescent images in the lens imply that some light is absorbed there. The loss of energy does not affect current experiments but will affect the economic analysis.

Various lasers have been used for the experiments reported in this quarter. We have found that the process is easily reproduced when new equipment is used; thus, the process must be insensitive to minor changes, as long as the beam envelope and intensity are constant. To assure beam quality, the intensity is profiled along the width and length for each set of experiments. Slits cut from graph paper are placed over the lens

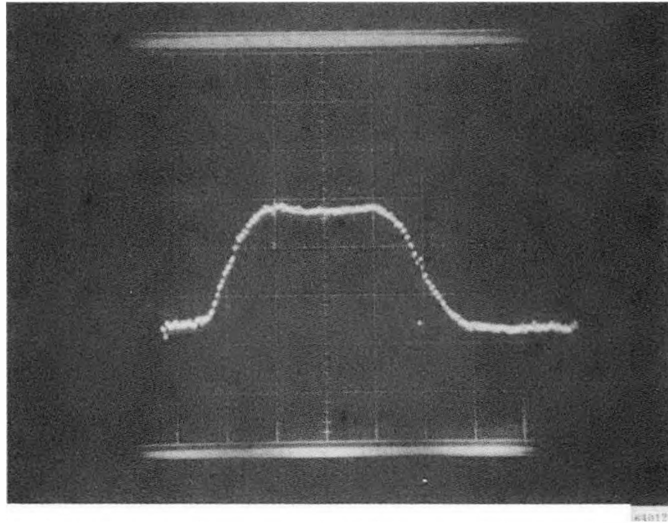

FIGURE 2. PULSED EXCIMER LASER BEAM INTENSITY (ARBITRARY SCALE) VERSUS HORIZONTAL DISTANCE (5 mm per division) AT OUTPUT LENS

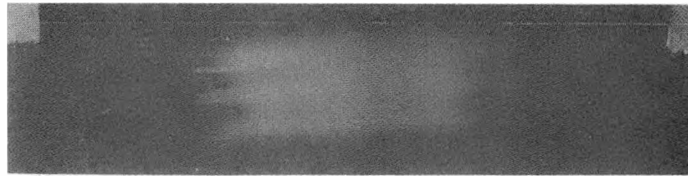

FIGURE 3a. BURN PATTERN FROM EXCIMER LASER AT FOCUSING LENS (APPROXIMATE FLUENCE 0.1 J/cm^2 AT 308 nm).

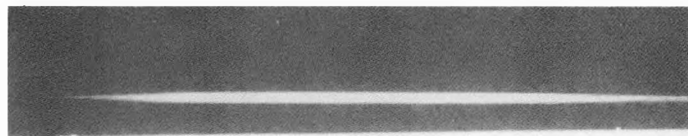

FIGURE 3b. BURN PATTERN FROM EXCIMER LASER AT SAMPLE POSITION (Same pulse as above, approximate fluence 1.0 J/cm^2).

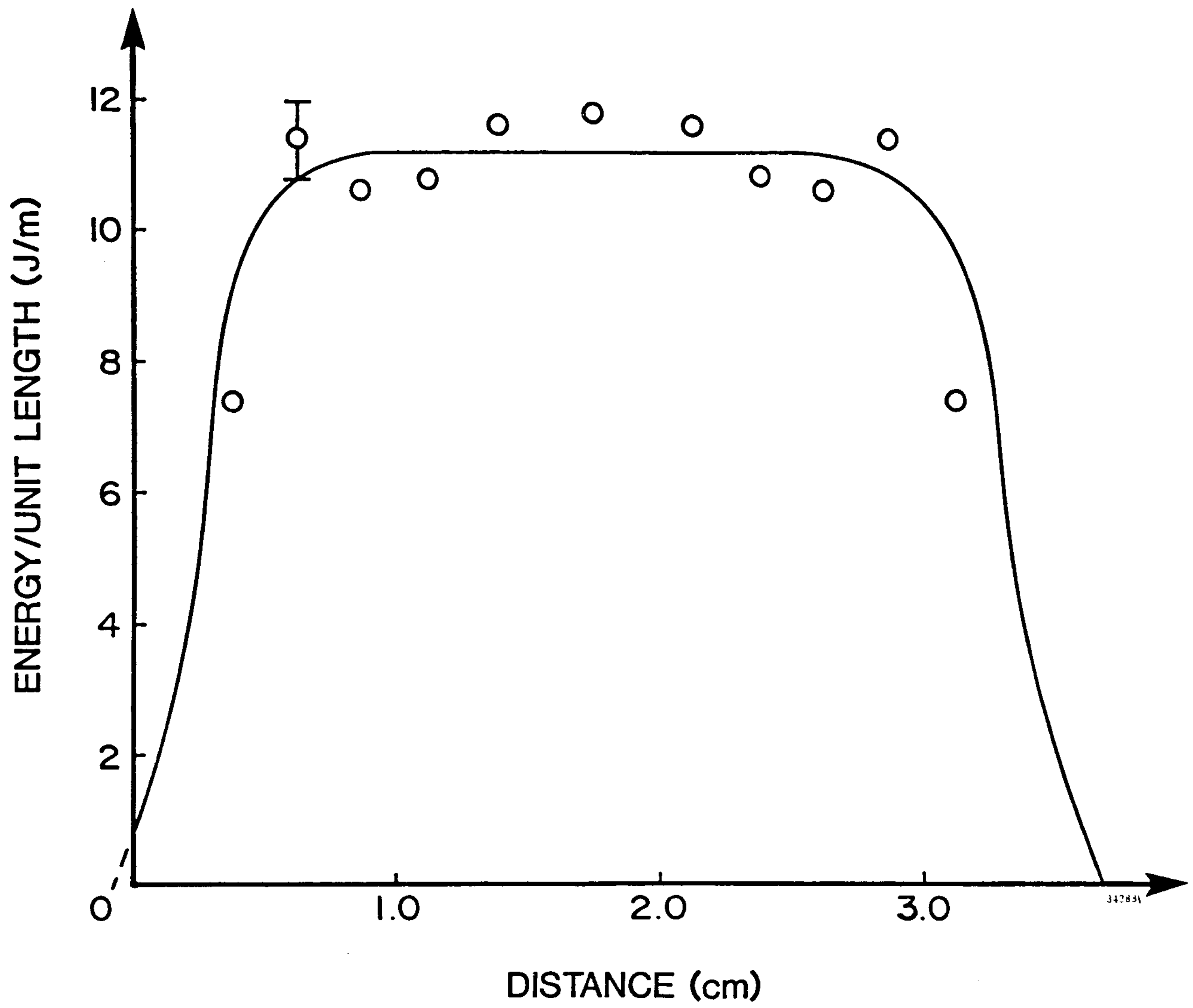

FIGURE 4. FLUENCE MEASURED ACROSS BEAM LENGTH HORIZONTALLY AT LENS.

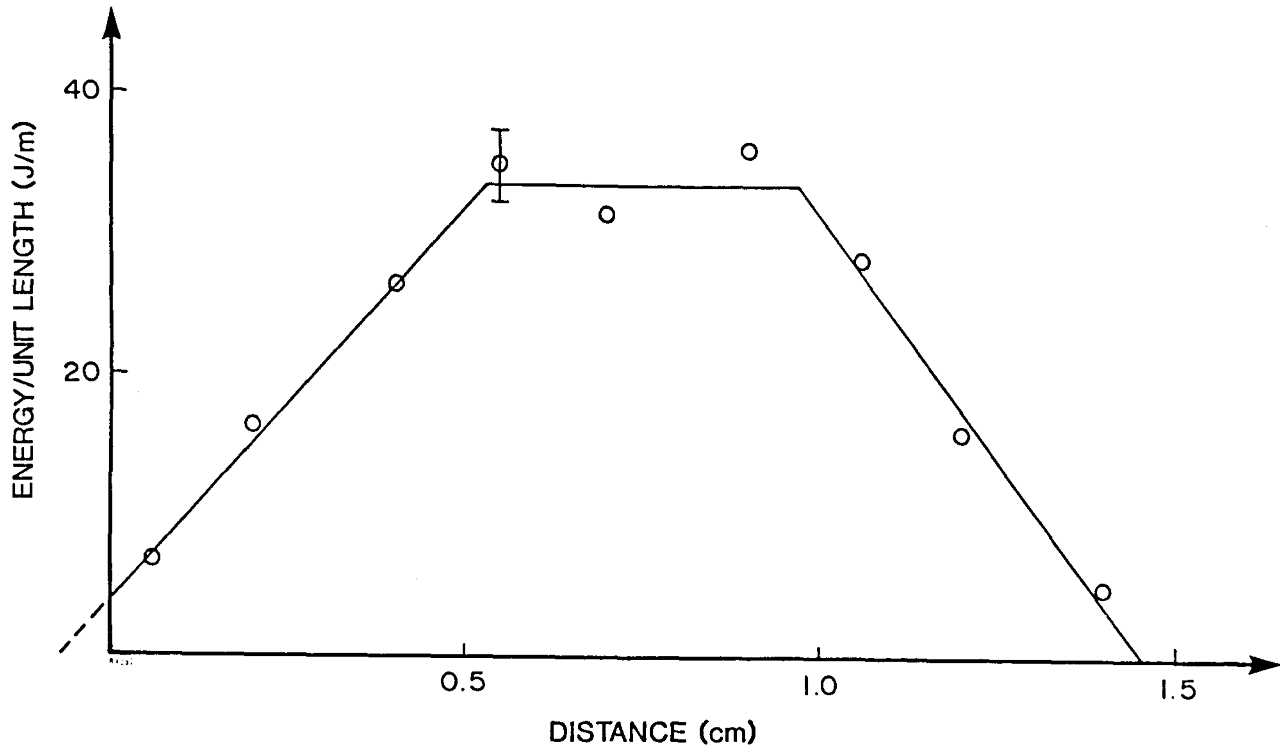

FIGURE 5. FLUENCE MEASURED ACROSS BEAM WIDTH VERTICALLY AT LENS.

with the power meter below it. Typical results are shown in Figures 4 and 5. Note that the horizontal profile in Figure 4, integrated across the full beam width, closely agrees with the profile in Figure 2, which measured only a narrow slice across the beam.

The fluence of the beam at the position of the sample cannot be measured directly as it is sufficient to damage most materials. It is inferred by dividing the measured intensity per unit beam length at the lens (Figure 4) by the beam width, which is measured using thermal sensitive paper (Figure 2b). A plot of beam width versus position of the focusing lens is shown in Figure 6. The average fluence estimated by this technique will be on the low side for the thermal paper is sensitive to 0.1 J/cm^2, and will make the region of uniform fluence (Figure 5) appear wider than it actually is. However, this line width correlates closely with the line width observed when a single laser pulse is used to anneal a high dose ion implant in texture-etched silicon.

The slow variation in beam width as a function of lens position (Figure 6) implies that the fluence, and final results, are not sensitive to this parameter. Micrometer adjustments of the lens height are unnecessary, as are especially fine adjustments of the angle of lens to the plane of the sample. Adjustments to aim the mirror were crude (turning the support bar in its bracket) but sufficient. Alignment of the laser beam to the plane of the mirror or sample was also not critical. The laser (or optical table in Figure 1) was moved on heavy wheels to align it and any position within 1/4 inch of center was acceptable.

2.2.2 Optimization of Front Junction Parameters

Experiments on Subtask 2 for polished surfaces and experiments on Subtask 3 for texture-etched surfaces were conducted in parallel. The starting material was float zone p-type silicon with a resistivity of 1.5 ohm-cm (100) orientation with one flat. One lot of 15 wafers (lot #4520) was cleaned and implanted with phosphorus at 10 keV to a dose of 2.5×10^{15} ions/cm^2. The backs of these wafers had etched surfaces. A second lot of identical material (lot #4519) was first texture-etched on both sides with an average pyramid height of 1 to 3 microns. The front surface was then implanted with phosphorus at 10 keV to a dose of 4.3×10^{15} ions/cm^2. The dose was calculated to give equal doping levels in both types of surfaces.

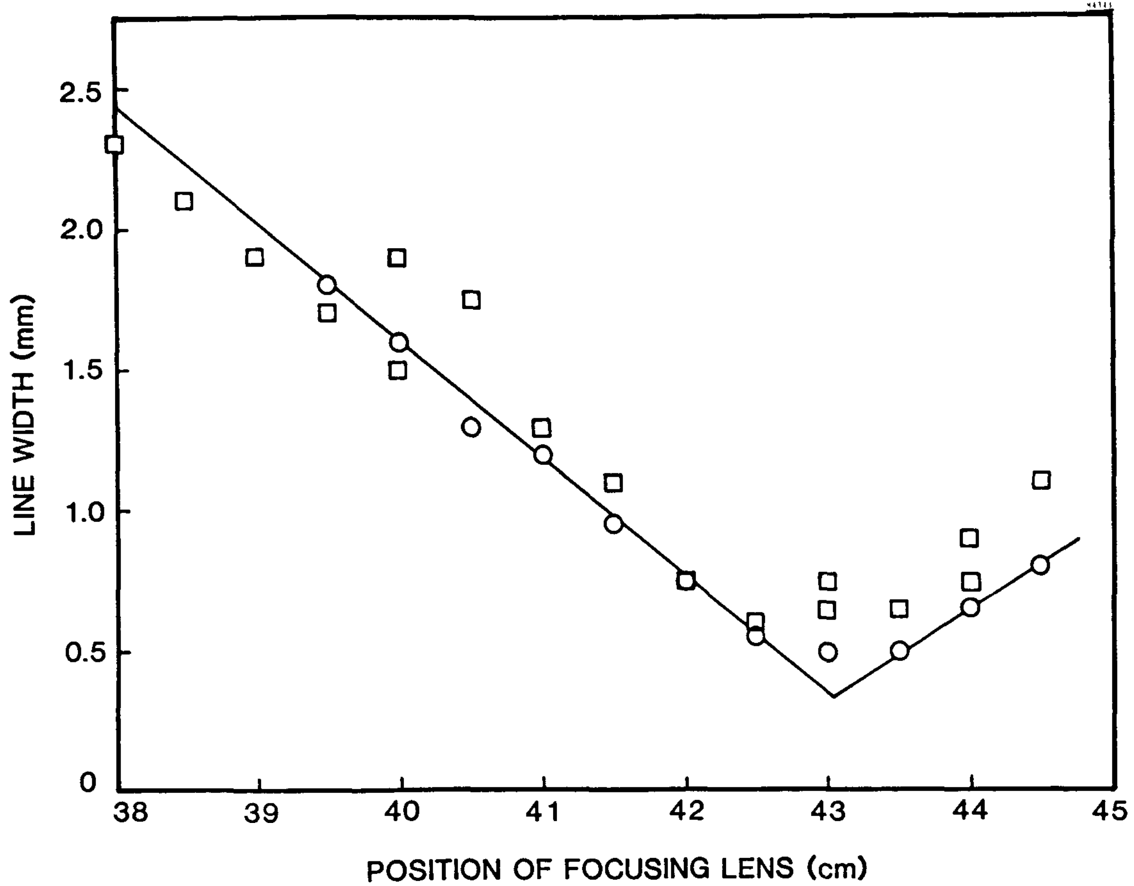

FIGURE 6. MAXIMUM LASER LINE WIDTH AT SAMPLE AS A FUNCTION OF LENS POSITION
400 mJ pulse energy
O 308 nm light, 2 inch chuck
□ 248 nm light, 4 inch chuck

Two additional groups of wafers from the same original lot of material were similarly prepared but with different back surface treatments. Lot #4539 had a polished front surface and etched back surface. The back was implanted with boron at 25 keV to a dose of 2.5×10^{15} ions/cm^2. These wafers were cleaned, then annealed in a furnace (2 hours at 550°C, 15 minutes at 850°C, 2 hours at 550°C) and then the front surface was implanted with phosphorus at 10 keV to a dose of 2.5×10^{15} ions/cm^2. Control cells in this lot were annealed a second time in the furnace using the same temperature-time profile. Lot #4540 was texture-etched on both sides and processed exactly like lot #4539 except that the ion implant dose ($4.3 \times 10^{15}/cm^2$ phosphorus and $5 \times 10^{15}/cm^2$ boron) was increased to account for the increased surface area of this material.

The excimer laser was filled with a mixture of krypton, flourine, and neon for the first experiment. The wavelength of the beam was 248 nm. Processing details and results were given in the first quarterly report for this program. These cells had a bad back contact. After applying the AR coating the back contact was etched off and reapplied on a selected group of cells (Table 2). Typical improvements in efficiencies with new contacts were from 12% to 13%. The best results given in Table 1 were still below values expected for this material and process.

The cell results in Table 2 were for 2cm x 2cm cells. Two cells labeled a or b were cut from each 2 inch diameter wafer. Measurements were made at AM1 illumination at 28°C. The line width given in the table was the approximate width of the annealed area of our laser pulse (±0.05 mm). The step size was the incremental distance moved by the scanning table between each pulse (±0.025 mm). The approximate fluence is the value of illumination in Figure 4 (0.11 J/cm) divided by the line width and normalized to the correct integrated laser output power.

Spreading resistance probe measurements were used to determine the uniformity of electrical characteristics and junction depth from wafer 4520-1. The best laser annealed cell in experiment number 1 (Table 2) came from this wafer. A piece near the corner of the anneal pattern, not on the cell, was used (Figure 7). To determine uniformity the sheet resistance was measured by stepping the probes across the surface, in 0.1 mm steps, parallel to the scanning direction. The actual sheet resistance from four point probe measurements was approximately 40 ohms/square. The spreading resistance

TABLE 2.

SELECTED CELL RESULTS FROM FIRST PELA EXPERIMENT WITH AR COATING

Lot/Cell	V_{oc} (mV)	J_{sc} (mA/cm^2)	Fill Factor (%)	Efficiency (%)	Approx. Fluence (J/cm^2)	Step Size (mm)	Line Width (mm)	Efficiency without AR (%)
4520 (Polished)								
1a	584	31.9	71.2	13.3	2.0	0.50	0.7	9.1
2a	589	32.1	70.3	13.3	2.0	0.50	0.7	8.9
5a	589	31.5	73.4	13.6	Furnace Control			9.1
5b	581	32.2	71.8	13.4	Furnace Control			9.1
15a	571	31.0	66.5	11.8	1.9	0.25	0.7	8.9
4519 (Texture-etched)								
3a	579	30.0	69.9	12.2	2.0	0.50	0.7	9.2
4a	576	29.5	62.8	10.7	1.8	0.25	0.7	8.2
6a	558	32.7	69.0	12.6	1.1	0.50	0.8	10.8
7a	543	32.5	69.9	12.3	1.2	0.90	1.10	10.5
8a	589	34.9	73.5	15.1	Furnace Control			12.9

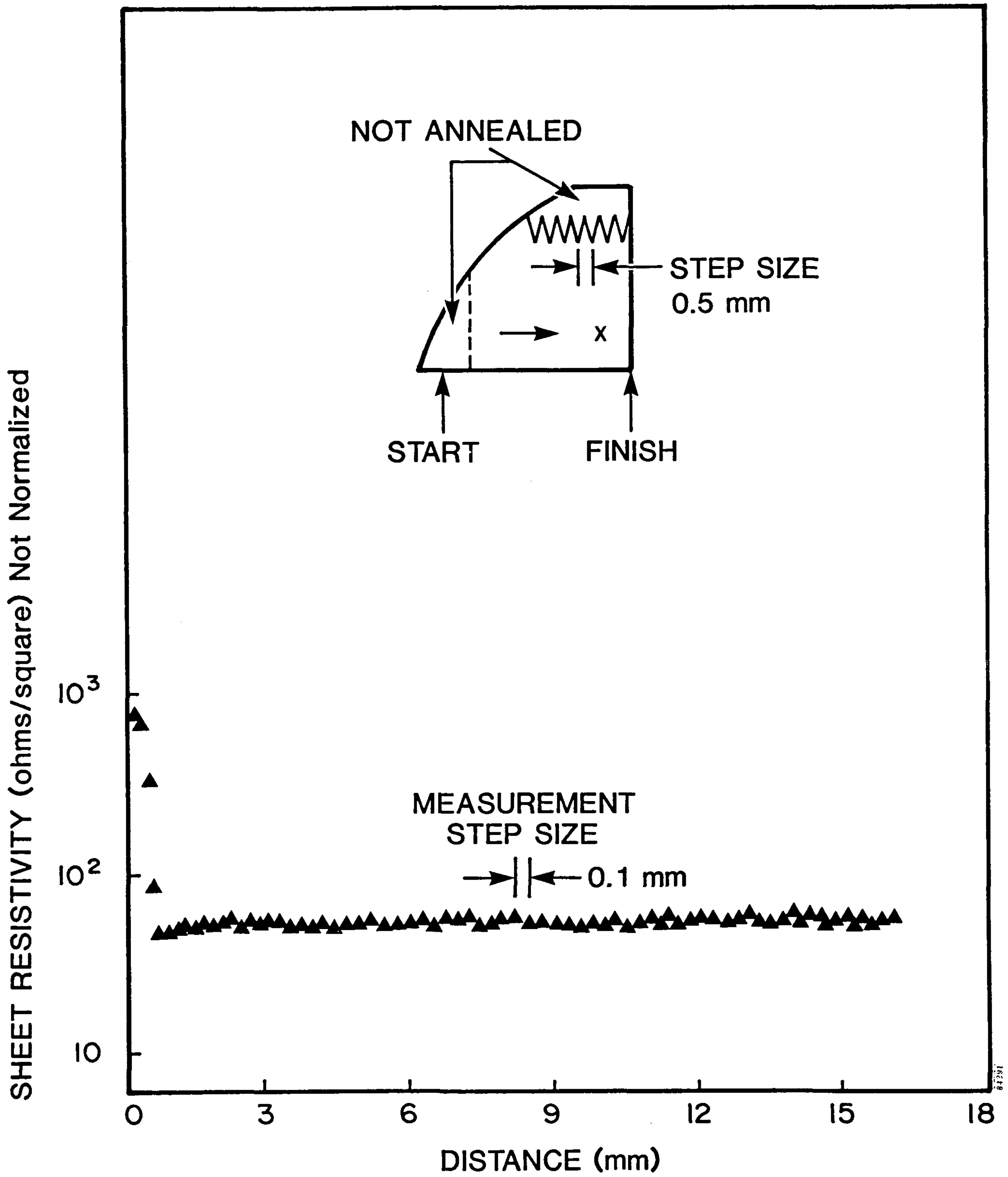

FIGURE 7. SHEET RESISTANCE UNIFORMITY OF PELA SAMPLE 4520-1.

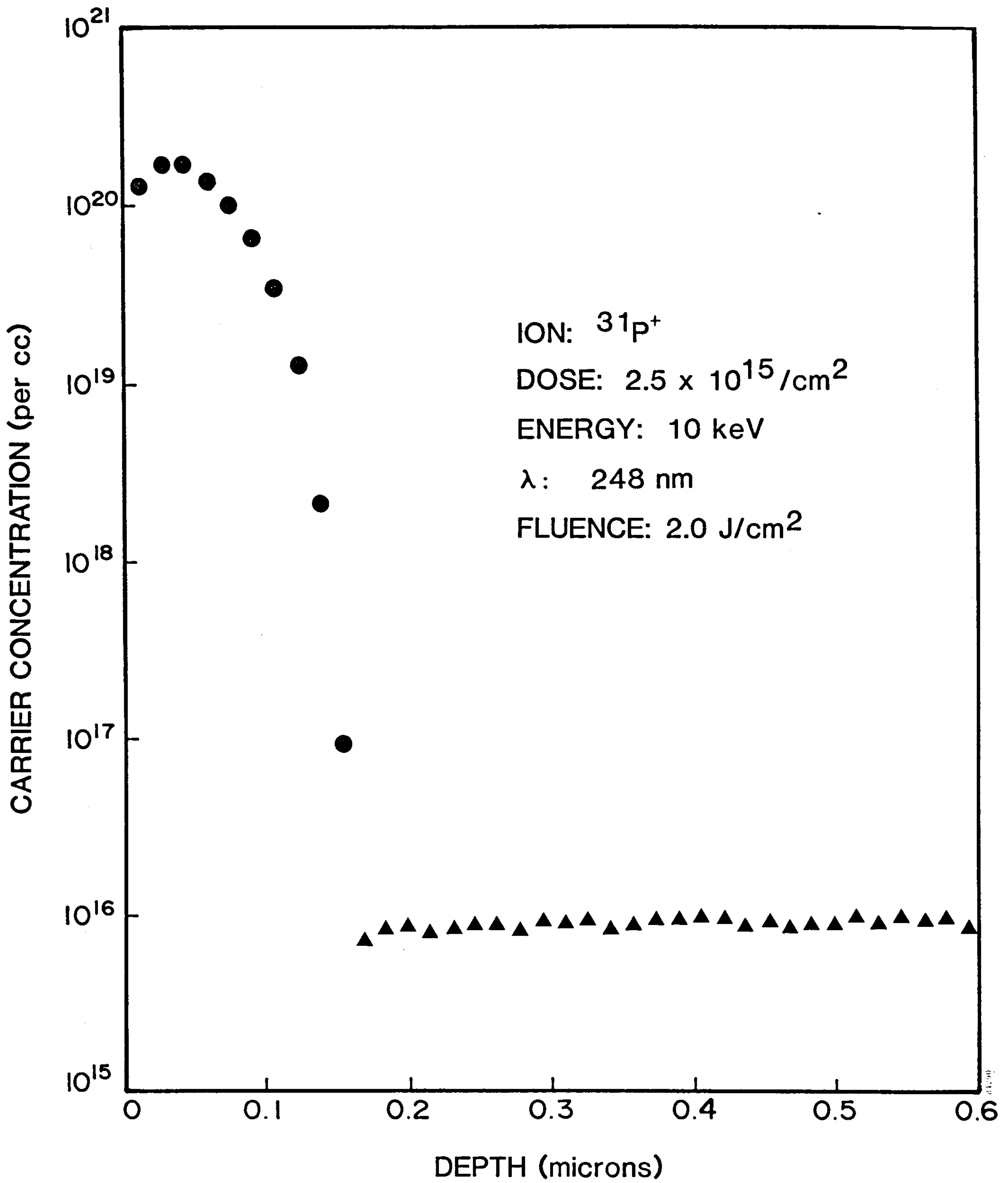

FIGURE 8. PELA JUNCTION DEPTH PROFILE SAMPLE 4520-1.

probes crossed many laser anneal spots which had a width of 0.5 mm. The measured resistivity was very uniform (Figure 7) and shows no pattern with 0.5 mm spacing. Note that the edge of the annealed region was very sharp. The carrier depth profile was measured (at point x in Figure 7) by beveling this piece. The results shown in Figure 8 indicated a very shallow junction. The junction depth for a tyical furnace anneal was 0.25 microns.

A different laser was used for the second experiment. It was filled with a mixture of xenon, neon, and HCl for 308 nm light output. The beam initially appeared uniform from its burn mark on thermal paper. However, the first four wafers processed (4519-9, 10, 12 and 4520-6) showed distinct linear features parallel to the scanning direction indicating non-uniformities in the beam. New optics were installed in the laser and processing was resumed. No similar patterns were visable on wafers 4519-1, 11, 13, 14, 15 and 4520-7, 8, 9, 10, 11 and 12.

Wafers used in this test were from the same lots used in the first experiment. After annealing, approximately 500 nm of aluminum was evaporated onto the backs of these cells and alloyed at 620°C for 5 minutes. Excess metal was removed prior to photolithography and evaporation of Ti-Pd-Ag. Measurements of cell parameters were made prior to AR coating (Table 3).

The furnace annealed control cells for this second experiment were poor. Contamination of the wafers during cleaning just prior to furance annealing is a possible but unconfirmed cause for the failure. All other processing of these cells, such as ion implantation, etching, or metallization, was performed simultaneously. The furnace annealed controls of experiment three (Table 4) fabricated with the same material and front surface ion implant parameters as experiment two are representative of the results expected of these controls.

The best result in the second experiment for polished wafers (4520-9b, Table 3) is comparable to the similar furnace control (4539-23b) in Table 4. This result was achieved at the highest fluence used, about 1.8 J/cm^2. The best result for texture-etched wafers (4519-14b, Table 3) was slightly inferior to the similar furnace annealed control (4520-21a, Table 4). The optimum fluence for texture-etched material was between 1.0 and 1.4 J/cm^2.

TABLE 3.

CELL RESULTS FROM SECOND EXPERIMENT
(NO AR COATING)

Lot	Cell	V_{oc} (mV)	J_{sc} (mA/cm^2)	Fill Factor (%)	Efficiency (%)	Approx. Fluence (J/cm^2)	Step Size (mm)	Line Width (mm)
4520 Polished	6a	545	23.0	65.4	8.2	1.0	0.25	1.0
	6b	542	22.6	65.8	8.0	1.0	0.25	1.0
	7a	534	22.9	61.8	7.6	1.1	0.25	1.0
	7b	534	22.8	61.0	7.4	1.1	0.25	1.0
	8a	580	22.2	79.1	10.2	1.8	0.25	0.6
	8b	580	22.0	79.5	10.2	1.8	0.25	0.6
	9a	578	22.9	78.8	10.4	1.8	0.50	0.6
	9b	578	23.0	78.6	10.5	1.8	0.50	0.6
	10a	557	23.3	74.2	9.6	1.0 to 1.4	0.50	1.1
	10b	560	23.4	74.2	9.7	1.0 to 1.4	0.50	1.1
	11a	529	22.5	59.0	7.0	0.8	0.50	1.4
	11b	532	22.4	61.4	7.3	0.8	0.50	1.4
	12a	537	20.9	66.7	7.5	Furnace Control		
	12b	537	20.8	66.4	7.4	Furnace Control		
4519 Texture-etched	1a	511	28.1	54.0	7.8	1.1	0.25	1.0
	1b	529	28.6	64.5	9.8	1.1	0.25	1.0
	9a	509	26.9	55.0	7.5	0.8	0.50	1.0
	9b	522	27.6	60.7	8.7	0.8	0.50	1.0
	10a	524	28.6	60.5	9.1	0.8	0.25	1.0
	10b	524	28.7	59.7	9.0	0.8	0.25	1.0
	11a	560	21.1	74.5	8.8	1.8	0.25	0.6
	11b	563	21.3	72.0	8.6	1.8	0.25	0.6
	12a	552	28.2	75.5	11.8	1.0	0.25	1.0
	12b	550	27.7	74.8	11.4	1.0	0.25	1.0
	13a	524	27.7	62.4	9.1	0.8	0.50	1.4
	13b	516	27.2	57.0	8.0	0.8	0.50	1.4
	14a	563	28.3	76.7	12.2	1.0 to 1.4	0.50	1.1
	14b	563	28.4	77.0	12.3	1.0 to 1.4	0.50	1.1
	15a	519	29.0	53.5	8.1	Furnace Control		
	15b	522	28.2	55.1	8.1	Furnace Control		

TABLE 4.

CELL RESULTS FROM THIRD EXPERIMENT
(NO AR COATING)

Lot/Cell	V_{oc} (mV)	J_{sc} (mA/cm^2)	Fill Factor (%)	Efficiency (%)	Approx. Fluence (J/cm^2)	Step Size (mm)	Line Width (mm)
4539 (Polished)							
23a	586	22.8	78.9	10.5	Furnace Control		
23b	586	22.8	78.6	10.5	Furnace Control		
24a	481	16.2	66.3	5.2	0.5	1.0	1.8
24b	481	16.0	66.2	5.1	0.5	1.0	1.8
25a	486	18.7	71.5	6.5	0.5	0.5	1.8
25b	483	18.2	71.9	6.3	0.5	0.5	1.8
4540 (Texture-etched)							
16a	478	27.8	65.2	8.7	0.6	0.50	1.8
16b	481	27.6	65.2	8.7	0.6	0.50	1.8
18b	476	27.4	68.5	8.9	0.5	0.50	1.8
19a	473	28.6	63.3	8.6	0.5	0.50	1.8
19b	450	28.4	50.8	6.5	0.5	0.50	1.8
20a	473	28.2	66.3	8.8	0.5	1.00	1.8
21a	558	30.4	76.3	13.0	Furnace Control		
21b	568	31.2	74.0	13.1	Furnace Control		

The efficiency of laser annealed texture-etched solar cells without AR coatings is affected by the change in reflectivity of the surface which occurs when the pyramids are partially melted. An integrating sphere and a Perkin-Elmer model 330 Spectrophotometer were used to measure the reflectivity from completed 2x2 cm cells with metalization but without AR coatings, and data is shown in Figure 9. The furnace annealed control cell from wafer 4519-15 (Table 3) has a reflectance of about 16% versus 33% for a polished furnace annealed control cell 4520-12 (Table 3). The texture-etched cell laser annealed at a high fluence (4519-11) has a reflectivity almost equal to the polished wafer whch can account for most of the difference between its efficiency and the 13% expected (4540-21, Table 4). With AR coatings, however, the efficiency of PELA cells on textured material in the first experiment was still not as good as that of PELA cells in polished material.

The third experiment was designed to determine the lower limit to the fluence that could be used for satisfactory annealing. Laser light of 308 nm was used in this test. It was performed before complete results were available from the second experiment. The data presented in Table 4 confirm previous results, that a minimum fluence of 1 J/cm^2 is required for pulsed excimer laser annealing.

A fourth experiment was initiated during the second quarter of this program to compare PELA results for 248 nm and 308 nm light. All silicon wafers were selected from the same lot, half were texture-etched. All material was implanted at the same time with identical back surface treatments. The laser output was checked at the lens to insure equal beam width, length and total power for both 248 and 308 nm light. The total energy in one pulse at either wavelength agreed within 0.3%. The focusing lens positions used were within 0.1 mm of predetermined values. The sheet resistance of wafers annealed during this experiment were measured (Table 5) and cell fabrication was initiated.

The results shown in Table 5 implied that the sheet resistance of polished wafers annealed at 248 nm was higher than that of wafers annealed at 308 nm. The sheet resistance of texture-etched material was generally lower (due to greater ion implant dose) and had greater scatter than that of polished material. The difference between results at 248 and 308 nm was interpreted as a change in fluence. The fluence quoted in Table 5 was based on the width of the central "hot spot" of the beam which

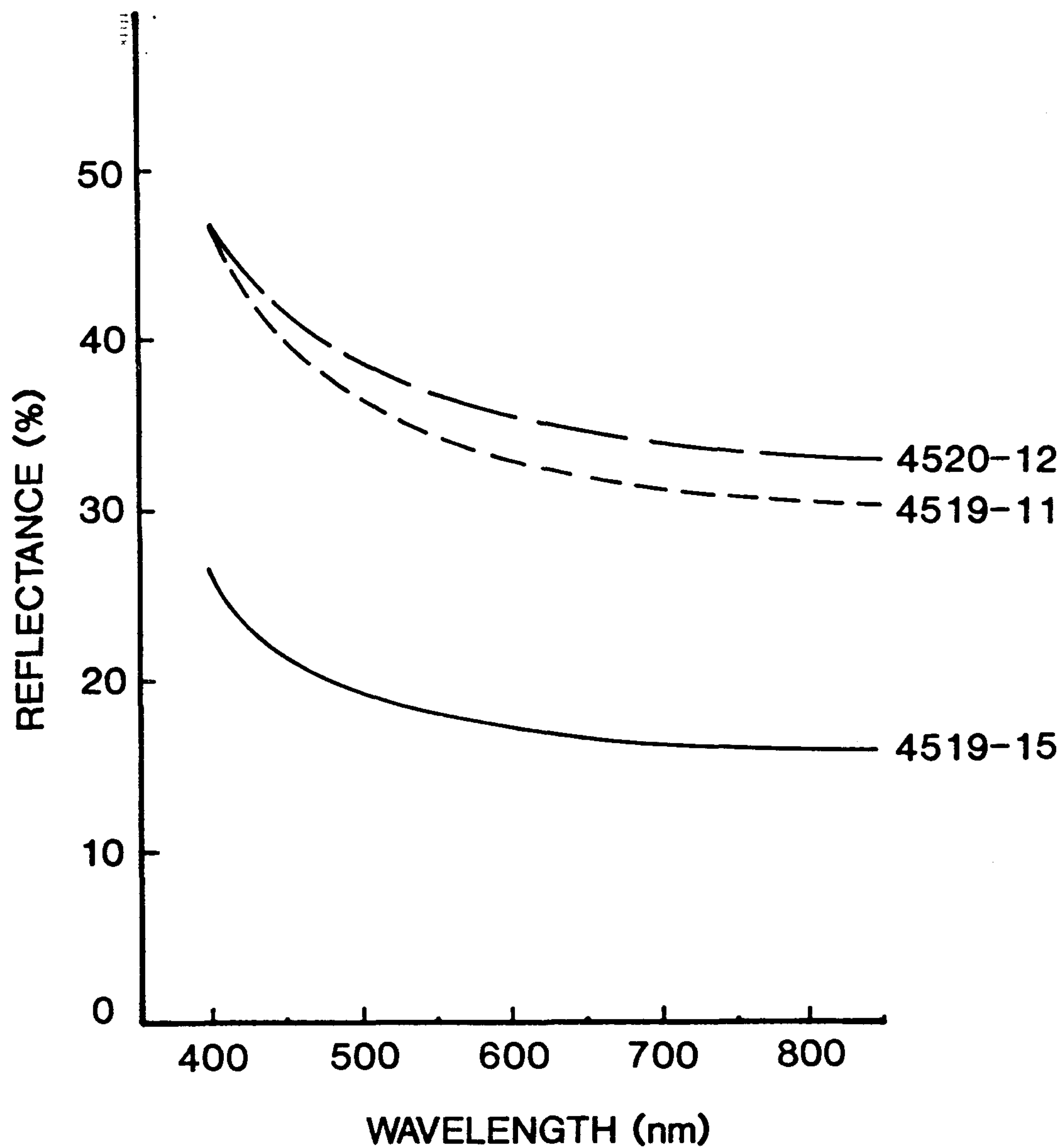

FIGURE 9. REFLECTANCE FROM 2x2 cm CELLS, NO AR Coating.
4520-12 Polished, furnace anneal
4519-15 Texture-etched, furnace anneal
4519-11 Texture-etched, laser anneal (1.8 J/cm^2)

TABLE 5. EXPERIMENT FOUR - COMPARISON OF PELA AT 248 nm and 308 nm LIGHT

Approximate Fluence (J/cm2)	Overlap (%)	Sheet Resistance (ohms/square)	
		248 nm	308 nm
Polished Wafers			
1.0	75	90	56
1.3	66	67	50
1.5	66	45	39
2.0	50	41	37
Texture-Etched Wafers			
0.8	66	59	45
1.0	75	26	39
1.0	66	26	44
1.3	66	46	36

was within ±.05 mm for the two wavelengths. However, the complete envelope of the beam was greater at 248 nm than at 308 nm (Figure 6) for all focal settings used. The cause for this difference, such as type of gas used or optical alignment, and its effect on cell results is not known.

2.2.3 Optimizing Parameters for Screen Printed Contacts

Work has just begun on this Subtask. A screen printer, appropriate screens, and a belt furnace for firing have been received from suppliers and are being set up.

2.2.4 Optimizing BSF Parameters

Three options are being considered for making the back contact to low resistivity silicon solar cells: (a) screen printed aluminum-doped ink, (b) drive-in of screen printed aluminum, (c) evaporated aluminum alloyed contacts, or (d) ion implantation and PELA. Option (a) is the least expensive and will be tested. Option (b) is the baseline process and will be tested. Option (c) has been tested (Section 2.2.2) and is acceptable. Option (d) requires optimization of parameters to PELA a boron or boron-triflouride implant.

Because the effect of a back surface field on a silicon solar cell in the 1.5 ohm-cm material used for tests in this program is minimal, optimization of laser parameters for annealing boron implants can best be done using a p^+nn^+ cell design. In the first experiment for this subtask polished n-type (4-11 ohm-cm) wafers were implanted on the back with phosphorus at 25 keV to a dose of 2.5×10^{15} ions/cm^2 and furnace annealed. They were then implanted on the front with boron at 5.6 keV or BF_2^+ at 25 keV, each to a dose of 2.5×10^{15}/cm^2 so that implant depth of boron would be nearly equal. Two wafers were set aside for furnace annealed controls while the others were laser annealed. Cell fabrication is progressing.

2.3 TASK (1)(C): DEMONSTRATE APPROPRIATENESS OF SOURCE

The objective of this task is to demonstrate the appropriateness of the specific excimer laser source selected to provide the pulsed energy required in the specific processes or process groups selected in Task (1)(A). This task is considered complete as an appropriate demonstration in the presence of a JPL observer took place this quarter.

The preliminary economic analysis for this process assumed that a 50 watt pulsed excimer laser from Questek would be sufficient to anneal a 10cm x 10cm square silicon wafer in less than six seconds. This corresponds to a throughput of 600 wafers/hour, equivalent to that of the non-mass analyzed ion implanter. In order to meet this throughput requirement, a plan for scanning a single wafer was devised (Figure 10) based upon laser power available and the maximum speed of precision stepper-motor driven X-Y translation stages. The scanning diagram assumes that each laser pulse can anneal a spot about 30 mm long by 1.1 mm wide. This allows for 10% overlap in the short and long directions. For a minimum fluence of 1.0 J/cm^2 the total energy reaching the wafer must be 330 mJ/pulse, or with a transmission efficiency of 80% through the focusing optics the laser output must exceed 410 mJ/pulse. The scanning diagram (Figure 10) implies that a pulse repetition rate of 100 Hz is necessary, or a laser output power of 41 watts. A laser power of 50 watts implies that the fluence on the sample with the proposed scanning diagram would be 1.2 J/cm^2.

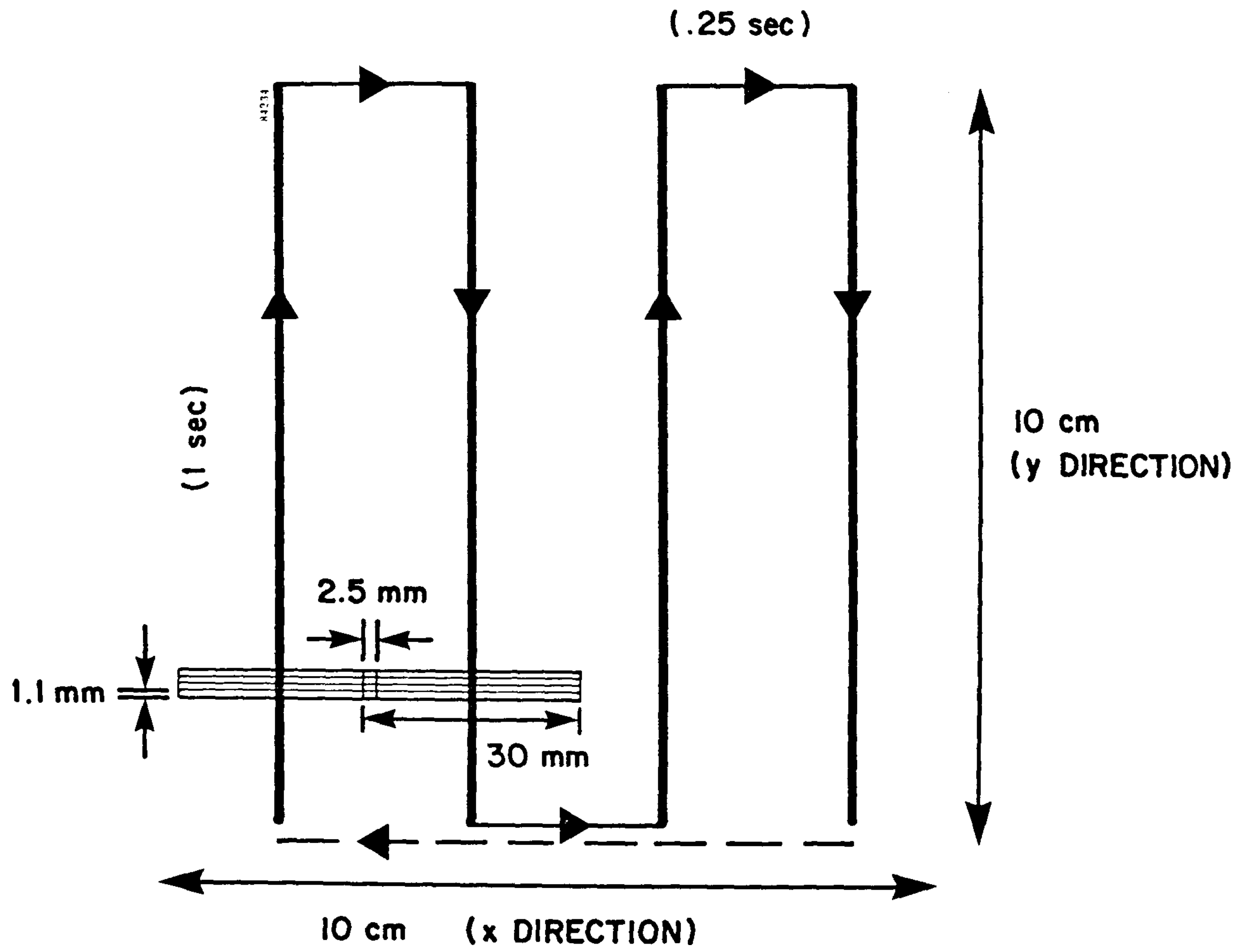

FIGURE 10. SCANNING PATTERN FOR ANNEALING A 100 cm^2 SQUARE WAFER (Total transit time at 10 cm/sec is 5.5 seconds).

The second experiment performed in this program showed that a fluence of about 1.2 J/cm^2, with a beam width of 1.1 mm (Table 3) annealed a texture-etched, ion implanted wafer. The length of this beam at the sample is about 30 mm (Figure 3b). The pulse size, fluence, and annealing characteristics having been proved, it only remained to show the required pulse repetition rate.

For this test a Questek laser with a KrF gas fill was driven at 50 watts output. The repetition rate of the laser was fixed at 160 Hz with a pulse energy of 312 mJ at the laser exit. To obtain a fluence exceeding 1.0 J/cm^2at the sample the beam was focused to a width of about 0.7 mm (43.4 cm setting in Figure 6) which allowed for 10% overlap at 160 Hz pulse rate and a sample speed of 4 inches per second. With these parameters the Questek laser successfully annealed a 10cm x 10cm polycrystalline silicon wafer, a 100 mm diameter texture-etched wafer, and a 100 mm diameter polished wafer.

During the actual high speed test the total time to complete the high speed scanning pattern shown in Figure 10 was 7.5 $\pm$.1 seconds. The discrepancy between this figure and the 5.5 second estimate is attributed entirely to a delay of approximately 0.5 second by the stepper motor controller every time it changed direction. This delay is used to activate a relay which can be used to control the laser. Different electronic controls can be used in production equipment to eliminate this delay, but we have not pursued the modification of the electronics of our laboratory apparatus.

In summary, it has been shown that a 50 watt output pulsed excimer laser can anneal ion implanted silicon at a maximum rate of 25 cm^2/sec. The throughput of commercial production equipment would be slightly lower, depending upon the duty cycle of laser beam utilization.

SECTION 3
CONCLUSIONS AND RECOMMENDATIONS

The determination of whether or not pulsed excimer laser annealing (PELA) is an economical alternative method of fabricating silicon solar cells will be decided entirely on the estimated achievable efficiency of the process in production. The cost per wafer of implementing this process may be twice as great as the cost of the equivalent element in the baseline process, but significant savings are realized for even marginal improvements in cell efficiency.

The initial experiments show that the PELA process is sensitive to surface preparation and alignment of laser optics, but relatively insensitive to focusing or scanning optics and ambient conditions. For polished surfaces the optimum anneaing fluence (20 ns pulse width) is over 1.8 J/cm^2. For texture-etched surfaces the optimum annealing fluence is between 1.0 and 1.4 J/cm^2. There may be minimal differences between using 248 versus 308 nm light. Alignment and care of internal laser optics is critical; beam dispersion (loss of fluence) and beam non-uniformities could be traced to the laser and not to focusing optics. All laser annealing experiments for this program are performed in air at room temperature under a laminar flow hood. The high speed annealing demonstration shows that a 50 watt laser is adequate for commercial production lines.

The maximum solar cell efficiency achieved by PELA was equal to that of the control, an ion implanted furnace annealed cell. We have not yet seen any evidence that PELA is better than this control process. However, the relative insensitivity of pulsed excimer laser annealing to many important process parameters implies that it has strong advantages over other pulsed annealing techniques such as Q-switched ruby or Nd:Yag lasers, and pulsed electron beams.

SECTION 4
PLANNED WORK IN THE NEXT REPORTING PERIOD

The research program is on schedule (Figure 10). In the next quarterly reporting period cell fabrication will be completed for ion implanted, laser annealed wafers comparing (a) 248 and 308 nm light anneals, (b) boron and BF_2^+ implant anneals and (c) 1.5 ohm-cm and 0.3 ohm-cm material. Also, laser parameters for annealing silicon wafers consistent with screen printed contacts will be defined, as well as parameters for annealing texture-etched material with 10 micron pyramid heights.

The back contact problem has been partially resolved as aluminum alloy backs give results comparable to furnace annealed ion implants in this material. Screen printing back contacts with aluminum doped inks will be tested in the next quarter. Also, because furnace firing of screen printed contacts requires deeper junctions, excimer laser sintering of dried but unfired ink patterns will be tested. Methods of improving the efficiency of the final cells will also be tested.

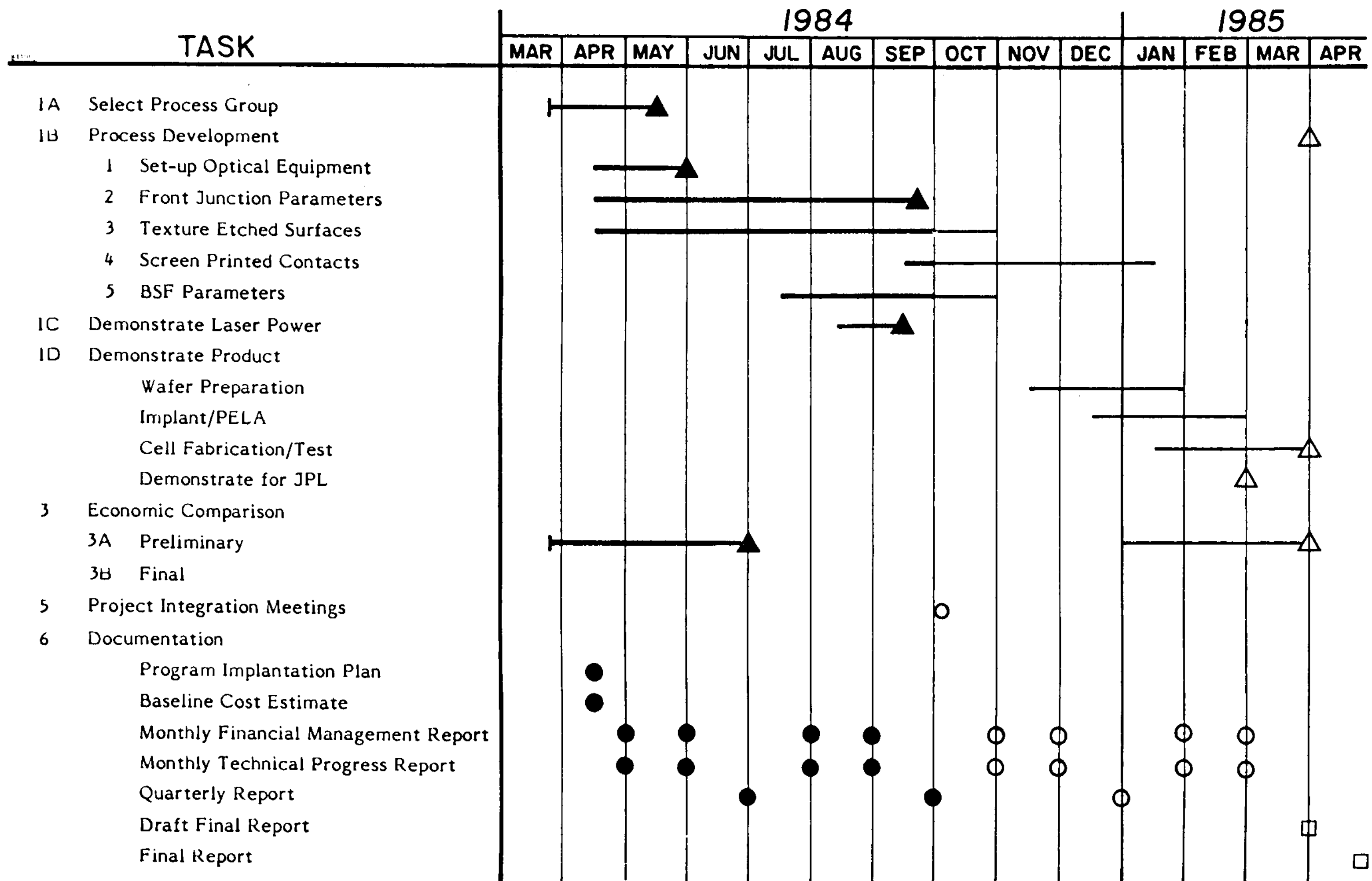

FIGURE 11. PROGRAM SCHEDULE

REFERENCES

1. R. T. Young et al. in Laser Solid Interactions and Transient Thermal Processing of Materials ed. J. Narayan, W. L. Brown, and R. A. Lemons, Material Research Society Symposia Proceeding V. 13 (North-Holland, New York, 1983) p. 401.

2. R. T. Young et al., Appl. Phys. Lett. 43, 666 (1983).

☆U.S. GOVERNMENT PRINTING OFFICE:1985-544-063/10811