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LASER ANNEALING OF ION IMPLANTED CZ SILICON FOR SOLAR CELL JUNCTION FORMATION

Final Report

By
J. S. Katzeff
M. Lopez

June 1981

Work Performed Under Contract No. NAS-7-100-955696

Lockheed Missiles & Space Company, Inc.
Sunnyvale, California

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The JPL Low-Cost Silicon Solar Array Project is sponsored by the U.S. Department of Energy and forms part of the Solar Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays. This work was performed for the Jet Propulsion Laboratory, California Institute of Technology by agreement between NASA and DoE.

FOREWORD

The results described herein represent the work performed from March 1980 to June 1981, by the Advanced Manufacturing Technology organization of the Space Systems Division, Lockheed Missiles and Space Company, Inc., Sunnyvale, California. The project leader was Mike Lopez, and the principal investigator was Jerry Katzeff. The JPL Contract technical manager was D. R. Burger.

Grateful acknowledgement is rendered to the major subcontractors of this program, William A. Butts and Anton C. Greenwald of the SPIRE Corporation, for the ion implantation and electron beam BSF annealing work, respectively, and Ken Ling and Scott Khemthong of Applied Solar Energy Corp., for the ohmic contacting anti-reflective coating and electrical testing work. Other support work thanks are extended to K. Monahan and T. Bardin of the Lockheed Palo Alto Research Laboratories, for the performance of RBS analysis, ARACOR for the TEM analysis, Charles Evans and Associates for the SIMS analysis, and finally, E. B. Boyce of the Advanced Manufacturing Technology organization for her invaluable assistance and cooperation in the preparation of the technical reports.

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Section 1

SUMMARY

An investigation was conducted which evaluated the merits of large spot size pulsed laser annealing of phosphorus implanted, Czochralski grown silicon for junction formation of solar cells. The feasibility and requirements were also determined to scale-up a laser system to anneal 7.62cm diameter wafers at a rate of 1 wafer/second.

A Quantel 30 Joule 20-50nsec Q-switched Nd:Glass laser was used in this investigation and was equipped with a frequency doubler which permitted operation at 1.06μm and .53μm wavelengths. A fused silica rod bent 90^{o} in the middle was used for beam homogenization yielding good uniformity across a 30mm diameter size spot.

Laser parameters were developed for optimized performance. These parameters were substantiated by surface analysis, including SIMS, TEM and RBS techniques, followed by fabrication of 2 x 2cm, 2 x 4cm and 7.62cm dia. functional cells to verify acceptability. Best junction formation parameters were ^{31}P ion implants at 5 KeV and a dosage of 2.5 x 10^{15}, a laser energy density of 1.5 J/cm^2, and 20nsec pulse duration.

Results show that laser annealing yields active, defect free, shallow junction devices. Functional cells with AM 1 conversion efficiencies up to 15.4% for 2 x 2cm and 2 x 4cm sizes were attained. For larger cells, 7.62cm dia., conversion efficiencies ranged up to 14.5%.

Experiments showed that texture etched surfaces are not compatible with pulsed laser annealing due to the surface melting caused by the laser energy. When compared with furnace annealed cells, the laser annealed cells generally exhibited conversion efficiencies which were equal to or better than those furnace annealed. In addition, laser annealing has greater throughput potential which is mandatory for the Low Cost Solar Array Project.

A high throughput pulsed laser system to accommodate single pulse annealing of 7.62cm diameter wafers at a rate of one (1) wafer per second is feasible.

Section 2

INTRODUCTION

This contract centered around the determination of the merits of large spot size pulsed laser annealing of phosphorus implanted, Czochralski (CZ) grown silicon wafers. An evaluation was also performed in determining the feasibility and requirements to scale-up a laser system to attain single pulse annealing of 7.62cm (3 inch) diameter wafers at a rate of 1 wafer/second, hence meeting the high throughput goals of the 1986 LOW COST SOLAR ARRAY PROGRAM.

The major thrust of the contract dealt with establishing optimum laser annealing parameters using the Lockheed large spot size pulsed laser system. Optimized parameters were verified by surface analysis coupled with fabrication of functional cells varying in sizes from 2 x 2cms to 7.62cm (3 in.) diameters.

The other elements of the process sequence used in the cell fabrication cycle, such as surface preparation, ion implantation, ohmic contacting and anti-reflective coatings, were performed by industry-established firms who had reduced these process steps to routine operations. SPIRE Corporation performed the ion implantation services and Applied Solar Energy Corporation (ASEC), the balance.

Cells were processed with and without back surface fields (BSF) for performance comparison. Those with BSF were ion implanted with boron bifluoride and electron beam annealed in order to restrict heating to substrate surfaces only. On some samples electron beam annealing was followed by laser annealing for additional data. Samples were also processed with an aluminum BSF consisting of screened on and fired aluminum paste. Three wafer surfaces were evaluated, namely - chem-polished, flash-etched, and texture-etched. These were evaluated with respect to the quality of cells produced using laser annealing.

For purposes of control and comparison with laser annealed devices, cells were fabricated with $POCl_3$ diffused junctions, as well as ion implanted and furnace annealed structures.

The laser system used for this investigation was manufactured by Quantel Int'l., and is a 30 joule, Q-switched Nd:GLASS laser, equipped with a frequency doubler, thus permitting operation at 1.06 and .53μm wavelengths. The pulse duration of the laser can be varied between 20 - 50nsec with a repetition rate of four pulses per minute (PPM). Beam homogenization was accomplished with a fused silica rod bent 90^{o} in the middle yielding a spot size of 30mm dia. The laser system is shown in Figure 1. Opaque side covers were removed to reveal the internal components. The optical path of the beam is shown in Figure 2. As can be seen, the laser consists of an oscillator and 6mm, 16mm, and 25mm amplification stages. The beam coming out of the oscillator (up to 180 millijoules) is progressively increased in energy in its passage through the amplifiers until it reaches its final energy of up to 40 joules (actual output exceeds rating).

Cell and laser annealing variables evaluated on the silicon wafers were as follows:

Wafer Specification:	CZ silicon, boron doped, 10Ω-cm <100>, 3-in. diameter, 0.014 in. thick.
Surface Condition:	Chem-polished, flash etched, and texture etched.
^{31}P Front Implantation:	5 KeV, $2.5 \times 10^{15} cm^{-2}$ 10 KeV, $2.5 \times 10^{15} cm^{-2}$ 10 KeV, $4 \times 10^{15} cm^{-2}$ (texture etched surfaces only)
Cell Processing:	Ion implanted, laser annealed with no back surface field. Ion implanted, laser annealed with back surface field.
Back Surface Field:	^{11}B and BF_2 implanted at 25 KeV, $5 \times 10^{15} cm^{-2}$, pulsed electron beam annealed (PEBA). Screened/fired aluminum paste.

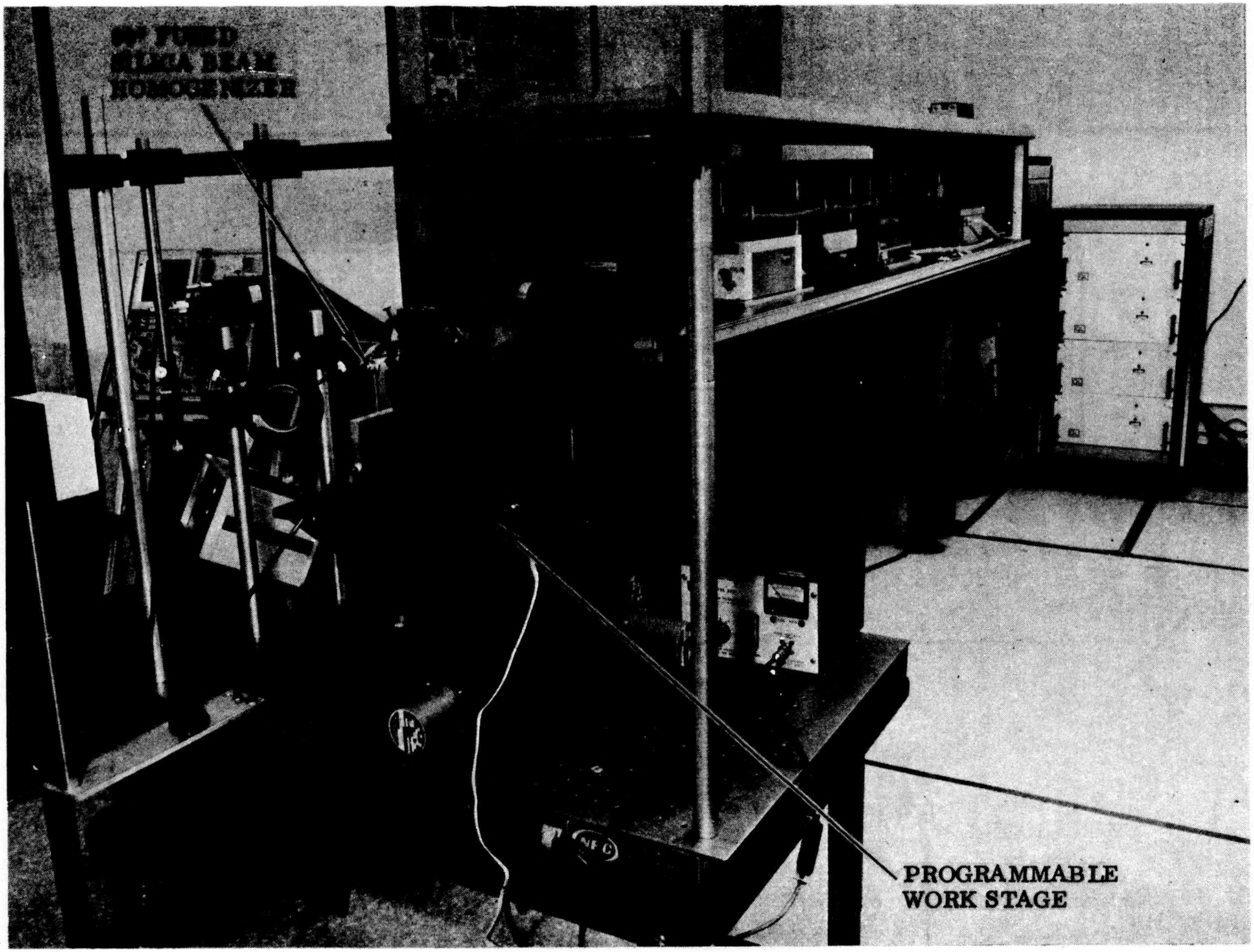


Figure 1. Laser System

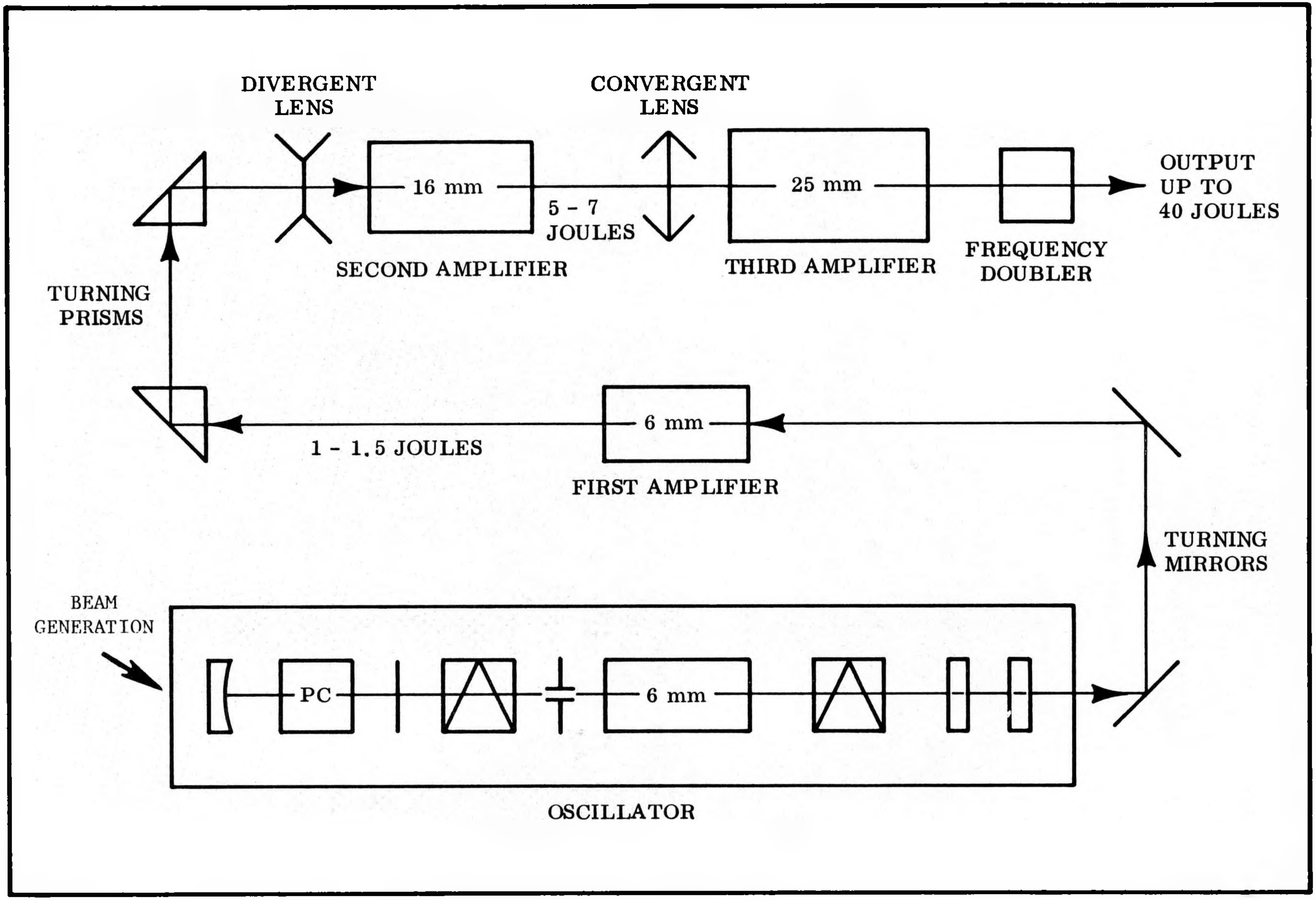


Figure 2. The Optical Path of the Laser

Front Anneal Variables: Laser energy densities of 1.2, 1.5, 1.9, and 2.1J cm^{-2} (all 30mm dia. spot size).

Control: $POCl_3$ diffused cells, chem-polished surface.

Ion implanted and furnace annealed using above implant levels, three surface conditions, with and without BSF.

Section 3

TECHNICAL DISCUSSION

3.1 WAFER MATERIAL AND SURFACE PREPARATION

The wafer material used on this contract consisted of the following:

- p type (boron doped), CZ silicon <100> orientation
- 7.62cm diameter in size x 0.036 $\pm$ .005cm thick
- 7 - 14 Ω-cm resistivity
- Surface conditions: texture-etched, flash-etched, and polished

The texture etching and polished surface processes are pretty well defined and documented. In view of previous work [1] there was concern that pulsed laser annealing was not compatible with texture etched surfaces, since the laser energy causes surface melting, and thereby destroys the pyramidal structures on the wafer. This concern was later substantiated based on additional work performed, whereby formed junctions were analyzed, and functional solar cells fabricated which were of inferior quality to those with polished or flash-etched surfaces. Details of this work are described in section 3.5.1.

Excellent results were obtained on polished surface wafers; however, the polishing process may not be a cost effective candidate process for the 1986 Low Cost Solar Array Project. Recently, processing improvements have been realized in this area by Applied Solar Energy Corporation (ASEC) by installing equipment yielding a production line capable of processing approximately 300 wafers per hour. It is believed that through further evaluation the line's throughput could be increased to qualify for the LSA Project.

Flash etching has been used successfully in the fabrication of solar cells. Intended for saw damage removal cnly, cells have been fabricated with respectable conversion efficiencies. The solution used for this investigation was the same as used in our Phase II, Automated Array Assembly contract [1] . It was supplied by JPL based on work performed by Photowatt (formerly Sensor Technology). The solution consisted of a mixture of Acetic, Nitric and Hydrofluoric acids in the ratios of 5:3:3 by volume, respectively, with immersion of the wafers for 30 seconds. This was followed by standard rinsing and drying.

Scanning electron microscopy (SEM) photomicrographs of texture-etched, chem-polished and flash-etched surfaces, representative of those used for this investigation, are shown in Figures 3 and 4.

3.2 LASER BEAM PROCESSING

The first step in the laser annealing investigation consisted of an evaluation of both the raw and homogenized beam modes of operation. The guiding philosophy behind this approach was to determine the minimum beam quality required which would still yield acceptably annealed structures at minimum costs.

3.2.1 Raw Beam Irradiation

For evaluating wafers annealed with a raw laser beam, it was planned in our investigations to hold the wafers in a horizontal plane, Figure 5, while reflecting the laser beam 90° onto the sample with the use of special high power laser mirrors. To this end three laser mirrors coated for reflectance at $\lambda=1.06\mu m$, $\lambda=.53\mu m$, and combination of $\lambda=1.06\mu m$, $.53\mu m$, were purchased from CVI Laser Corporation, one of the leaders in the high power laser coating industry. Post laser radiation exposure evaluations of the mirrors revealed coating degradation from hot spots in the laser beam on mirrors coated for $\lambda=.53\mu m$, and combination wavelength. It was concluded by CVI that beam hot spots exceeded the damage threshold of the coatings, and that since these were the highest damage resistant coatings available, no obvious solution was apparent.

To alleviate the mirror problem, it was decided that laser annealing could be performed without the aid of the mirrors if the wafers were properly fixtured in a vertical plane. Figure 6 depicts the projection of the beam with the wafer mounted vertically, with the aid of a vacuum fixture. The fixture, Figure 7, made of aluminum offered excellent hold down of the 7.62cm diameter wafers, and had been found extremely useful in irradiating test samples. The aluminum reflected the laser energy and was not adversely affected. This set up permitted evaluations of samples annealed with a raw beam.

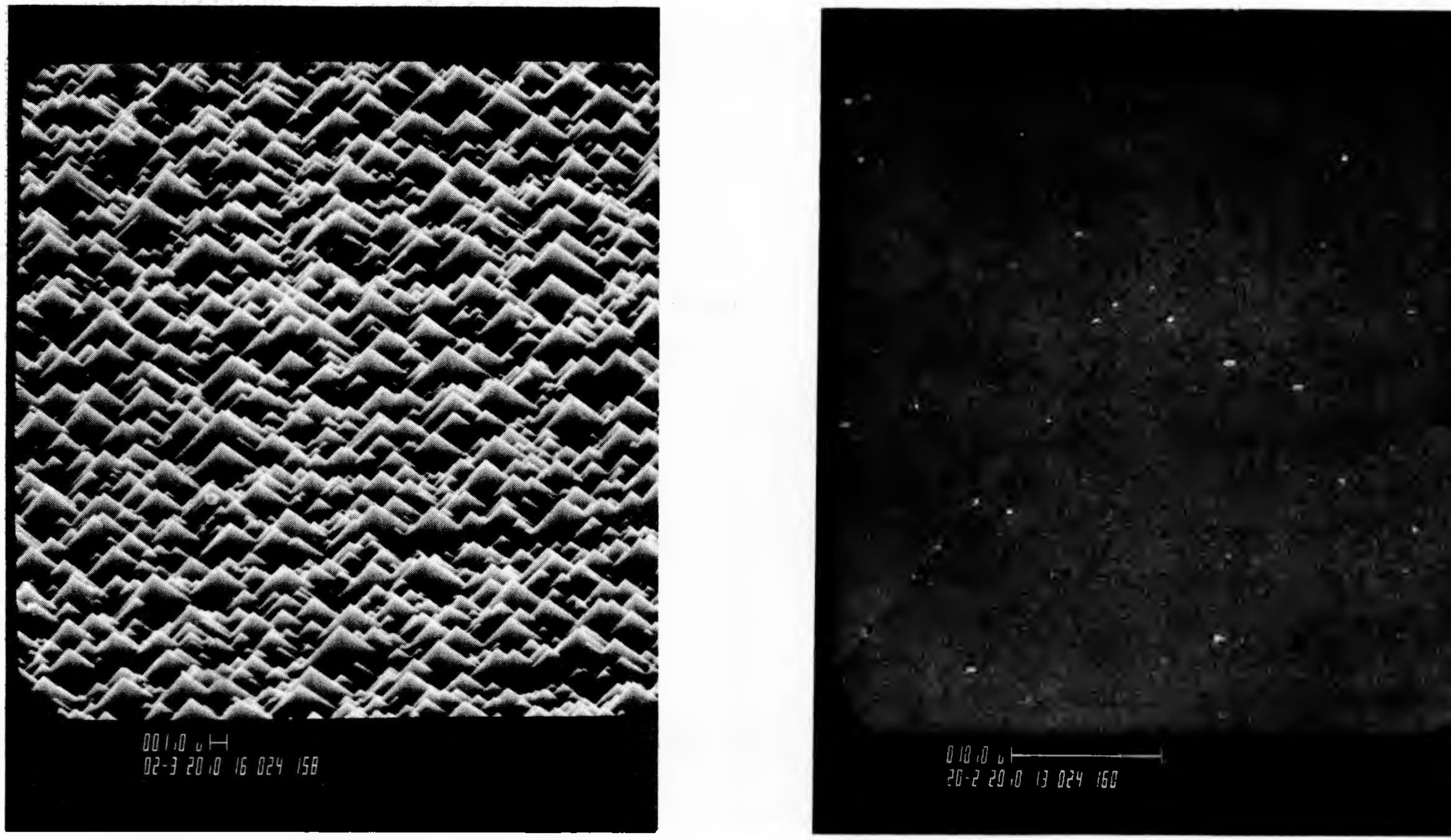
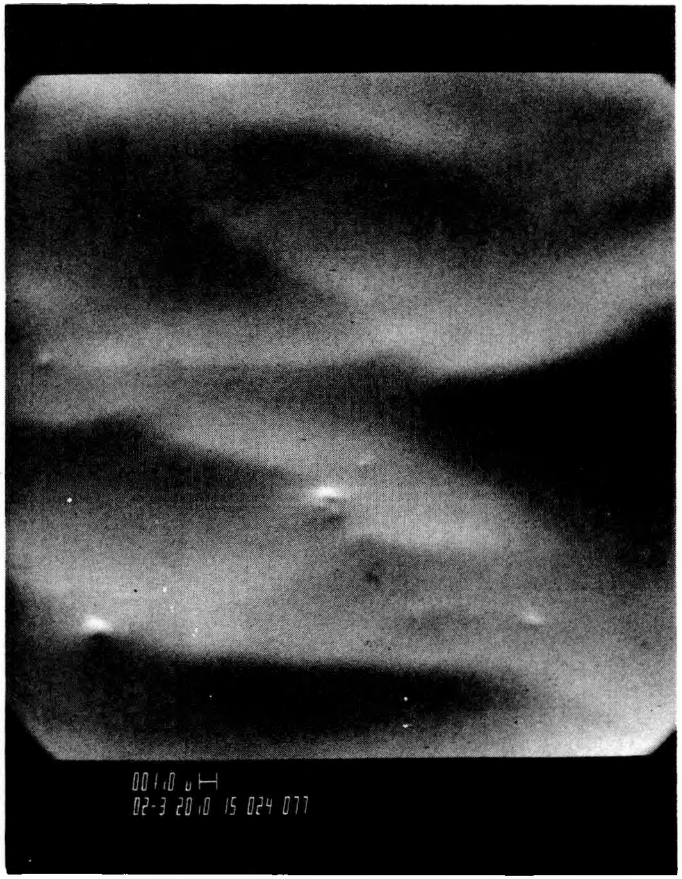
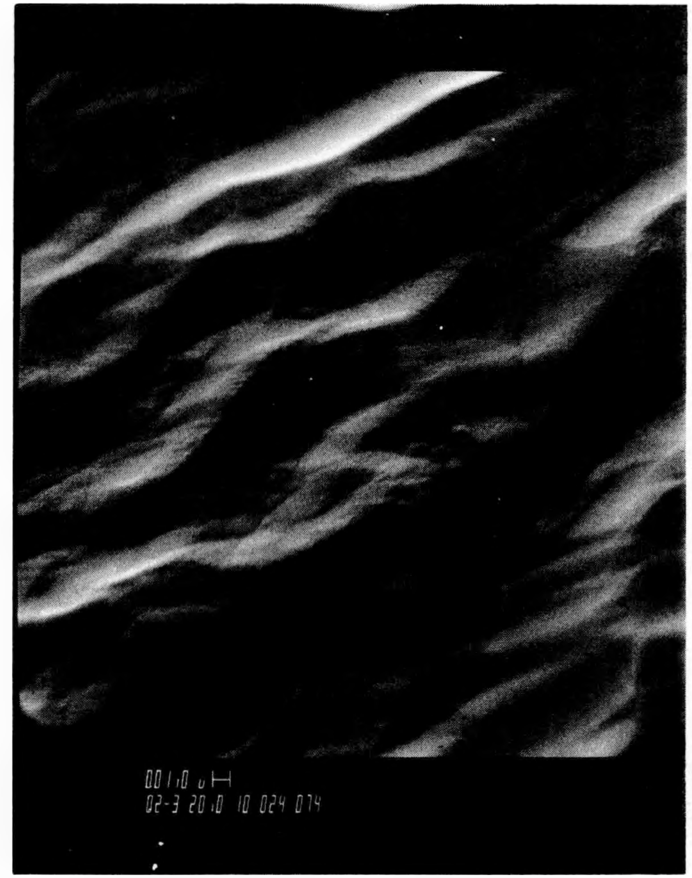


Figure 3. SEM Photos,Texture Etched (left) and Chem Polished (right) Surfaces
2000X 60^{o} Tilt



Wafer Center View



Wafer Edge View

Figure 4. SEM Photo, Flash Etched Wafer Surface
2000X 60^{o} Tilt

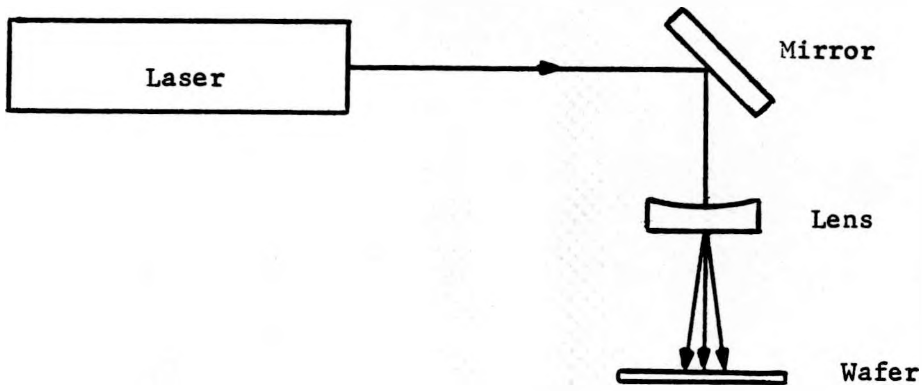


Figure 5. Configuration of optical components for bending the laser beam 90° onto the sample wafer.

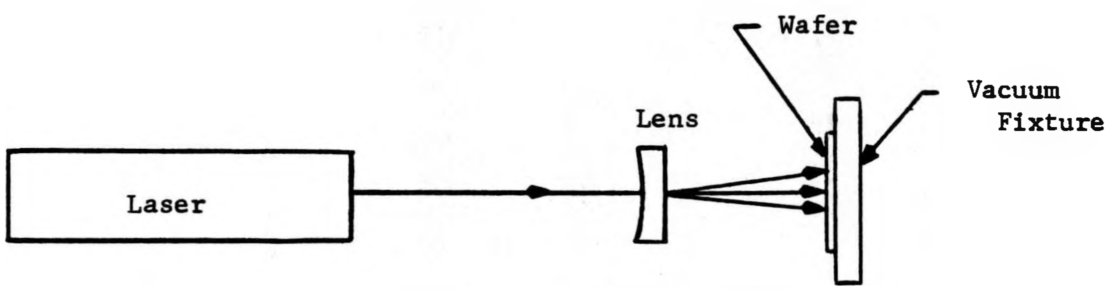


Figure 6. Configuration of components for vertical positioning of sample wafer.

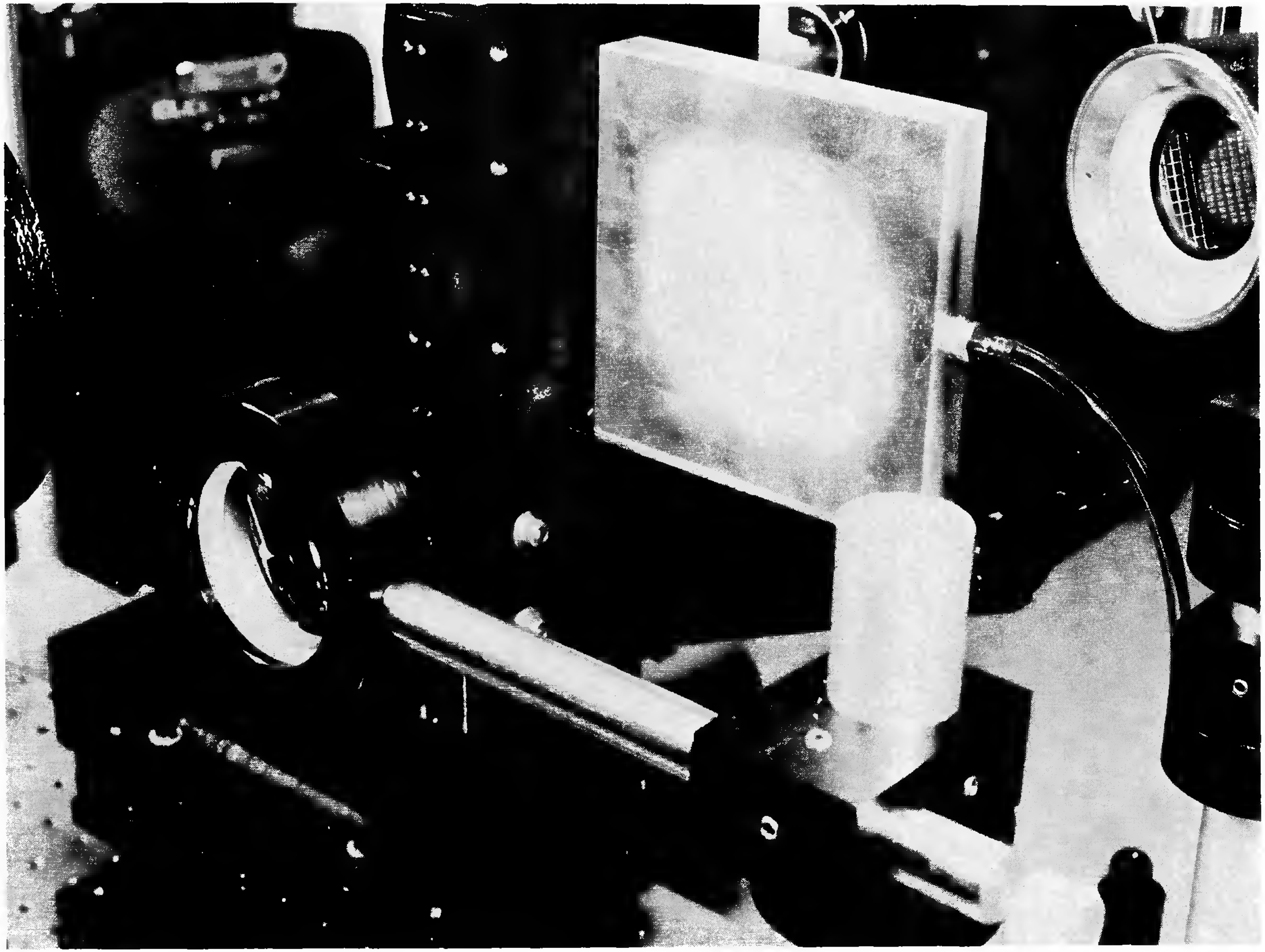


Figure 7. Lens and vacuum fixture set up for holding a wafer in a vertical plane during laser annealing

Preliminary evaluations of laser annealing utilizing the raw beam output were initiated on wafers implanted at 25 KeV, 3 x 10^{15} ions/cm^2 of ^{31}P. These wafers were available from our previous in-house work on laser annealing. To obtain maximum anneal area coverage, a -100mm focal length plano-concave lens was used to diverge the laser beam.

The lens utilized was made from BK7 glass with double peak AR coating. Both the substrate and the coating were damaged by the laser beam, which led to experimentation with uncoated fused silica lenses with an inherently higher damage threshold than BK7 glass.

Laser exposure tests have shown that the fused silica lenses have excellent stability and damage resistance. However, the tests also revealed two other potential problems. The reflectance of the uncoated lenses is approximately 8%, representing a potential for damage to the laser oscillator from the reflected beam. To alleviate this problem, the lens was tilted at an angle to ensure that the beam would not be reflected back into the system. The second problem was discovered in processing the sample wafers. The annealed area on each wafer exhibited a small circular spot that was untouched by the laser radiation. It was discovered that the presence of this spot was also due to the high reflectance of the uncoated lenses. The laser beam reflected from the concave surface of the lens was focused to a point with sufficient energy density to ionize the air at that spot with the result that the created plasma was opaque to laser radiation. This condition was propagated to the surface of the wafer, as shown in Figure 8.

The condition of having an unannealed area on the wafer presented a problem only in fabricating cells from single pulse annealed silicon with a raw beam. In cases where multiple pulses were utilized, either on the same spot or through step and repeat procedure for large area coverage, the problem was eliminated by rotating the wafer in the case of the former, and using sufficient overlap in the case of the latter.

The problem could also be eliminated by using lenses with long focal lengths. A small tilt angle imparted to such a lens placed the focal point outside the path of the incident beam, Figure 9, hence eliminating the "blind spot" condition. To this end lenses with -300mm and -500mm focal length were purchased, and wafers were annealed and evaluated. The evaluation consisted of sample visual and RBS analysis of the specimen in the center and edges of the annealed areas. RBS analysis revealed that annealing with a raw beam is not uniform due to the gaussian nature of the beam. With the energy concentrated in the middle of the beam, a potential for surface damage also existed. In addition since no homogenizing medium was utilized, high intensity spots in the beam also caused wafer surface damage. Finally all the optics in the laser annealing system had to be absolutely spotless, and damage free, since any optical fault on the optics would be propagated to the wafer under irradiation. In view of the difficulties with raw beam annealing it was decided, therefore, to evaluate a homogenizing system which would yield uniformly annealed regions and remove the critical necessity of having to utilize totally "unblemished" optical components.

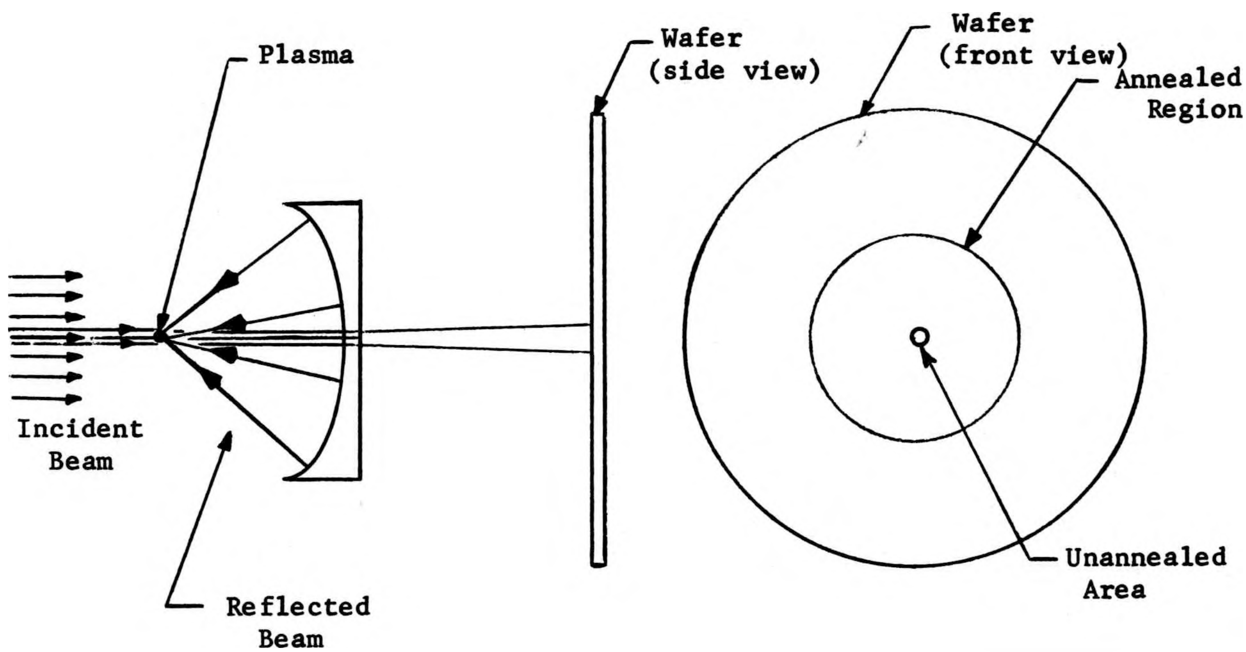


Figure 8. Formation of an unannealed spot on a wafer due to uncoated lens created plasma.

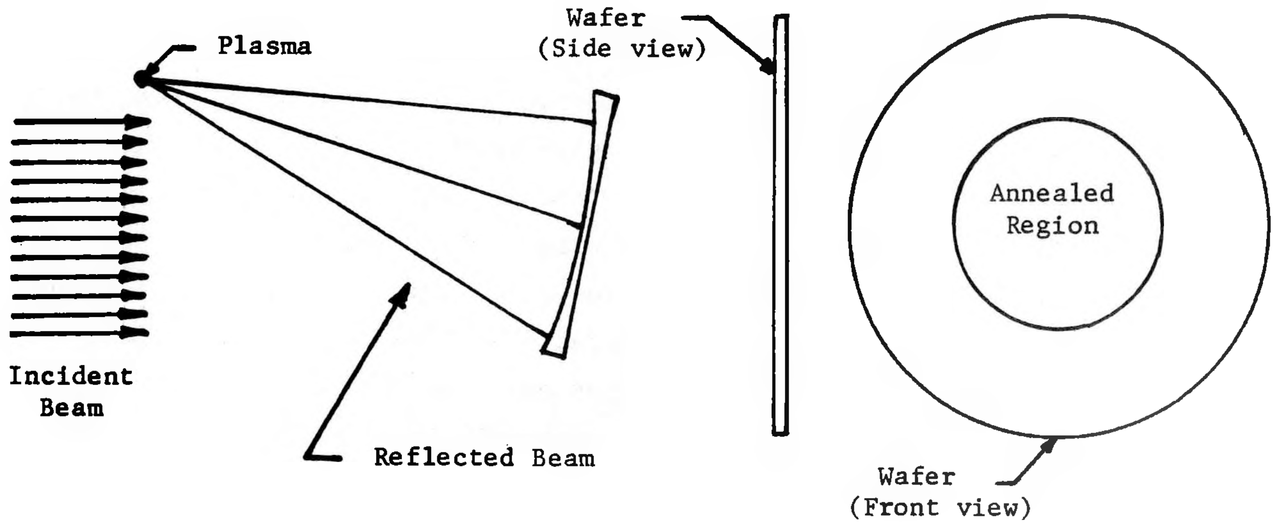


Figure 9. Elimination of an unannealed spot on a silicon wafer by tilting a long focal length plano-concave lens.

3.2.2 Homogenized Beam Irradiation

The obvious advantage of raw beam annealing is that the laser beam is directly coupled to the target and hence there are no transmission losses as would be observed if the beam was passed through a homogenizing medium. The problem, however, is that with a raw beam certain limitations are inherent when annealing with single high power Q-switched laser pulses due to intensity inhomogeneities in the beam. The presence of a mode pattern also yields large intensity variations which can degrade annealing uniformity. In a Gaussian beam distribution associated with TEM_{00} mode operation, unwanted specimen damage could occur in the regions subjected to the central (maximum power) portion of the beam.

To attain satisfactory beam homogenization, an optical system was developed [2] to eliminate inhomogeneities in high power laser pulses. The system, called a light guide diffuser, consists of a fused silica rod bent approximately 90^{o} in the middle, Figures 10 and 11. The laser output beam is directed to the input face of the rod, which is ground with diamond powder or equivalent. As the beam enters the light guide, it is diffused, although some microscopic intensity inhomogeneities remain. Most of the incident light is scattered close to the forward direction and passes down the guide being subsequently contained by total internal reflection at the guide wall.

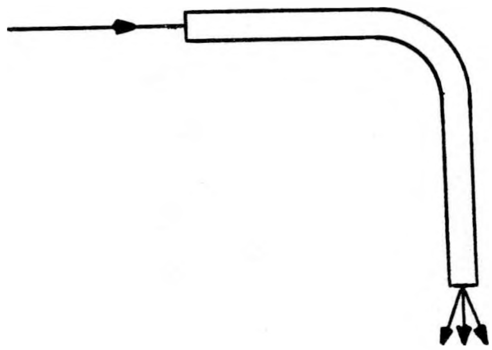


Figure 10. Light Guide Diffuser Schematic

A relatively small proportion of the incident light is scattered through large angles at the input face and is lost. As the radiation propagates down the guide, repeated internal reflection further diffuses the beam and speckle components are progressively eliminated. This process is enhanced, especially for near-axis light, by introducing a curve into the guide. A bend of approximately 90° has been found to be particularly effective in suppressing any remaining speckle while giving rise to minimal light losses. However, such bends introduce caustic patterns into the transmitted light and a further length of guide is required to re-homogenize the beam. The light finally emerges from the guide through an exit face which is normal to guide axis and highly polished.

Initial results with a prototype light guide diffuser indicated that very good beam homogenization was obtained. Figure 12 shows laser beam burn spots on photographic paper produced by the "raw" beam in (A) and by the homogenized beam in (B).

The central gray area in the raw laser burn spot corresponds to the maximum beam energy. The progressively darker regions moving radially away from the center, are indicative of progressively lower energies typical in a Gaussian beam distribution. The burn spot in (B), however, is of a uniform shade corresponding

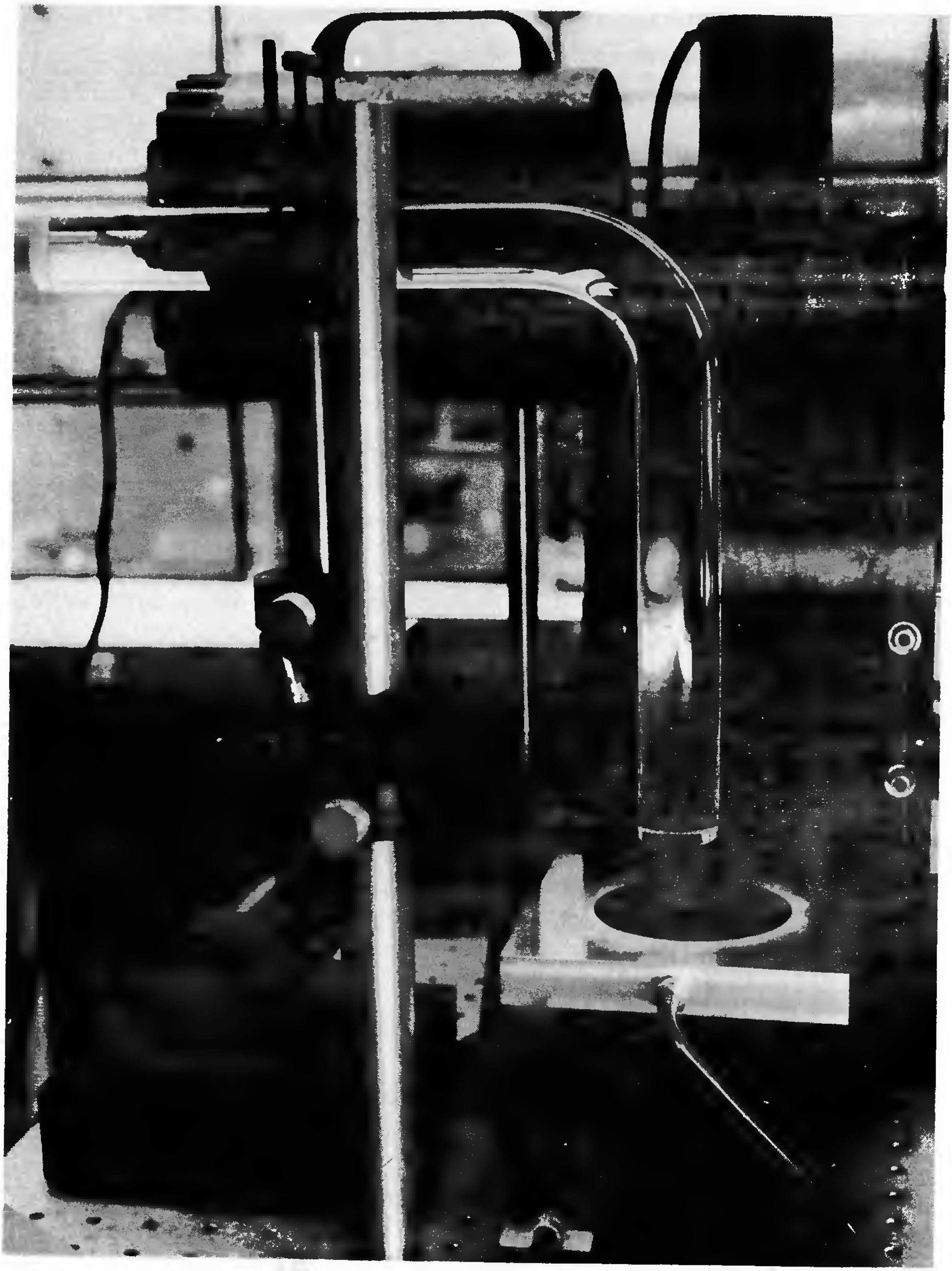


Figure 11. Light Guide Diffuser

to a homogeneous energy output obtained with the light guide diffuser. Anneal uniformity was further substantiated by Rutherford Backscattering analysis which showed an almost identical spectrum across the full 30mm spot size. Typical light intensity losses experienced with this homogenizing system were approximately 35%.

(A) (B)

Figure 12. Laser burn spots on photographic paper from a "raw" beam in (A) and homogenized beam in (B) - approximately 25mm diameter.

Figure 13 shows 30mm diameter annealed regions on a 7.62cm diameter flash etched wafer. For reference, a 2 x 2cm cell was placed on one of the annealed spots indicating existing capability of single pulse annealing for fabrication of 2 x 2cm solar cells.

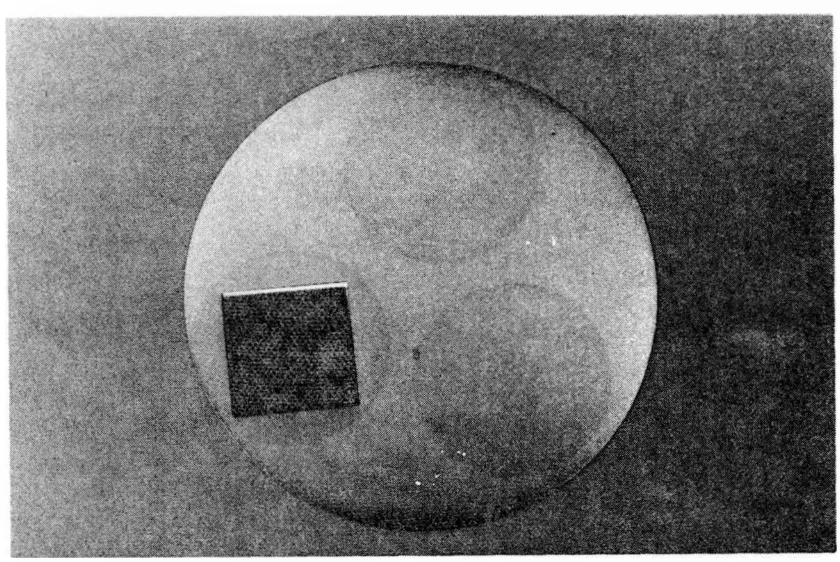


Figure 13. Single pulse 30mm diameter anneal areas on a 3-inch diameter silicon wafer. A 2 x 2cm cell is included for reference.

In an attempt to minimize light losses, another system was evaluated using quartz tubes. The attractiveness of this approach rested in the fact that the light losses incurred are minimal in comparison to those incurred with a light guide diffuser (silica rod). In this evaluation a plano-concave lens was placed in front of quartz tubes coated with aluminum or silver. It was assumed that laser light diverged by the lens would be contained by the quartz tube with final spot size to be determined by the diameter of the tube. Figure 14 illustrates this concept. Tubes obtained and evaluated were eight (8) inches in length by 30, 35, 40 and 45mm inside diameters with wall thicknesses of 2mm. Difficulties were experienced with the tube coatings blowing off due to the high absorption of the laser energy. Also, there was constant propagation of high intensity spots onto the silicon substrate which damaged the wafer surface. At this point, rather than undertake an extensive development effort with the tube concept, it was decided to abandon this approach in favor of the bent fused silica rod. The rod has demonstrated excellent beam homogenization characteristics, and was used for the balance of the contract work. It is felt, however, that additional work should be performed on other homogenization approaches, including tubes, but with separate funding resources.

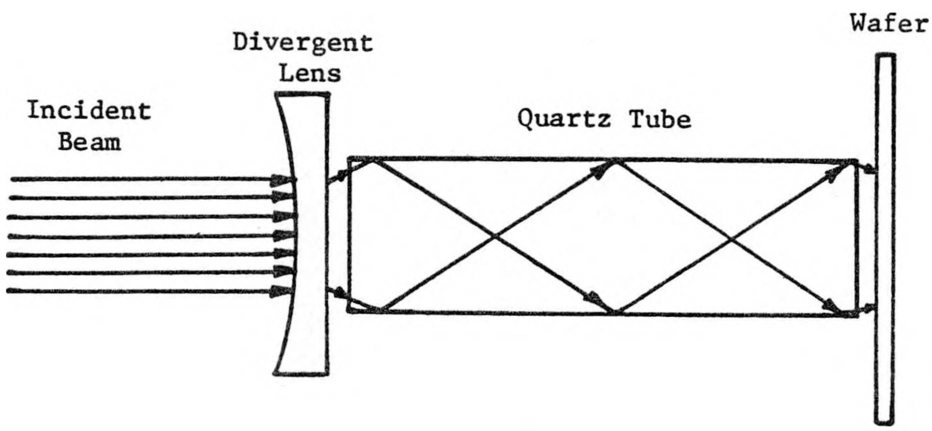


Figure 14. Utilization of a quartz tube for controlling shape and size of anneal area on a wafer.

3.3 LASER ANNEAL PARAMETER DEVELOPMENT

3.3.1 Laser Parameter Selection

The laser annealing parameters evaluated are shown in Table 1.

Table 1

LASER ANNEAL PARAMETER VARIABLES

Wavelength (μm)	Pulse Width (nsec)	Laser Energy Density J/cm^2
1.06	20-50	1.2
.53		1.5
		1.9
Combination 1.06/.53		2.1

Best optical coupling of the laser energy into the silicon was obtained with the laser operating in a dual wavelength 1.06μm/.53μm mode. Laser energy at .53μm is deposited in the immediate surface region - raising the temperature and hence absorption of the surface layer. At this point, improved surface coupling of the 1.06μm energy occurs with the result that lower anneal energy density is required at the combination wavelength as opposed to annealing at 1.06μm only.

Annealing with a 20nsec pulse width proved to be advantageous to annealing at 50nsec The conversion efficiency of the frequency doubler is a function of peak power. Twenty-five percent conversion efficiency was attained with a 20nsec pulse, and only 15% with a 50nsec pulse. Since the .53μm energy improves the optical coupling to the silicon of the 1.06μm energy, reduction in energy and peak power of the former, leads to reduction in the surface layer absorption of the latter. To compensate for this considerably higher energy, density settings had to be utilized to produce equivalent results with a 50nsec pulse as compared to 20nsec pulse operation.

Once the optimum pulse width and wavelength mode of operation were established, investigations turned to determining the laser energy density required for annealing the ion implanted substrates. To this end, the four energy density settings shown in Table 1 were evaluated, and the irradiated substrates subjected to Rutherford backscattering (RBS), Transmission Electron Microscopy (TEM), and Secondary Ion Mass Spectrometry (SIMS) analysis. Obtained data (see Section 3.3.2) indicated that complete silicon recovery from implant induced damage was attained at all of the above energy densities.

3.3.2 Removal of Ion-Implantation Induced Damage

Analysis by RBS techniques, Figure 15, shows $^4He^+$ backscattering and channeling spectra for random aligned, as-implanted, laser annealed (1.5J/cm^2) and unimplanted (virgin) silicon. The as-implanted spectrum shows a broad peak which corresponds to the depth of the disordered layer in the silicon introduced by the implanted specimen. Analysis of the laser-annealed implant shows a backscattered spectrum almost identical to that of virgin silicon, indicating complete lattice recovery with no evidence remaining of the phosphorus-induced damage.

The TEM results for laser annealed silicon is shown in Figure 16. The data is essentially identical for all the laser anneal energy densities listed in Table 1. For comparison, a TEM micrograph of a furnace annealed (900^{o}C/20 min.) sample is also included. Single crystal diffraction patterns (upper-right insert) were obtained for both samples, indicating recrystallization and recovery from the amorphous state during laser and furnace annealing. The laser annealed implant was found to be defect free, whereas considerable defect density was found in the furnace annealed specimen.

The SIMS analysis to study the effects of laser annealing on the dopant distribution, Figure 17, showed that the dopant diffusion is a function of laser anneal energy density. It was obvious from the data that to maintain shallow junction conditions in the cell, annealing should be carried out at laser energies no greater than 1.5J/cm^2. Formation of a shallow junction in the solar cell is advantageous in view of the improved spectral response (at the blue end of the spectrum), resulting in higher cell conversion efficiency.

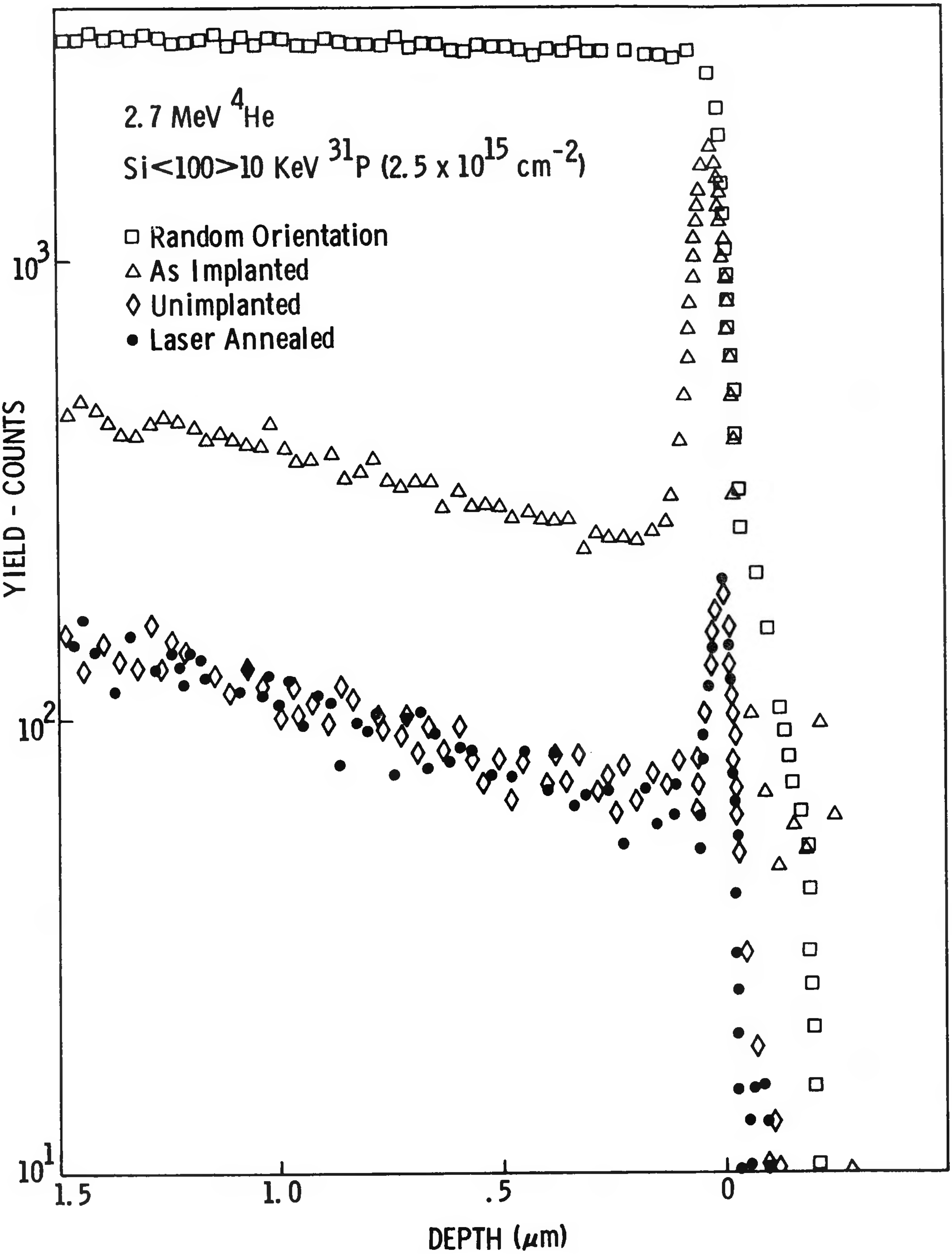
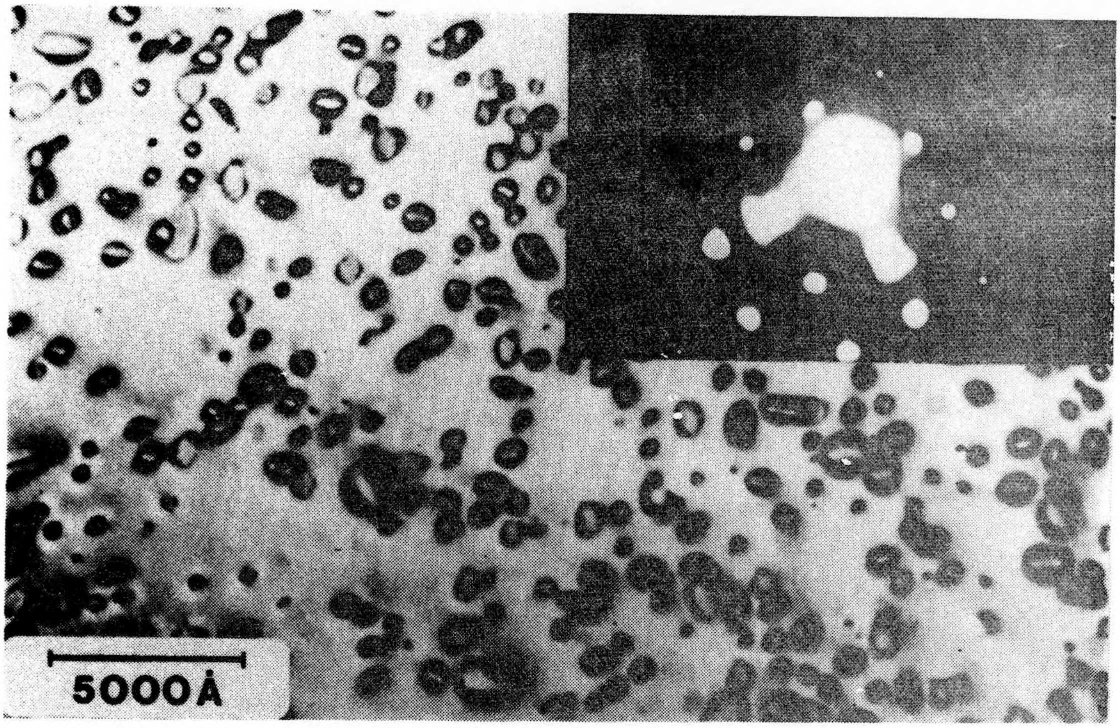
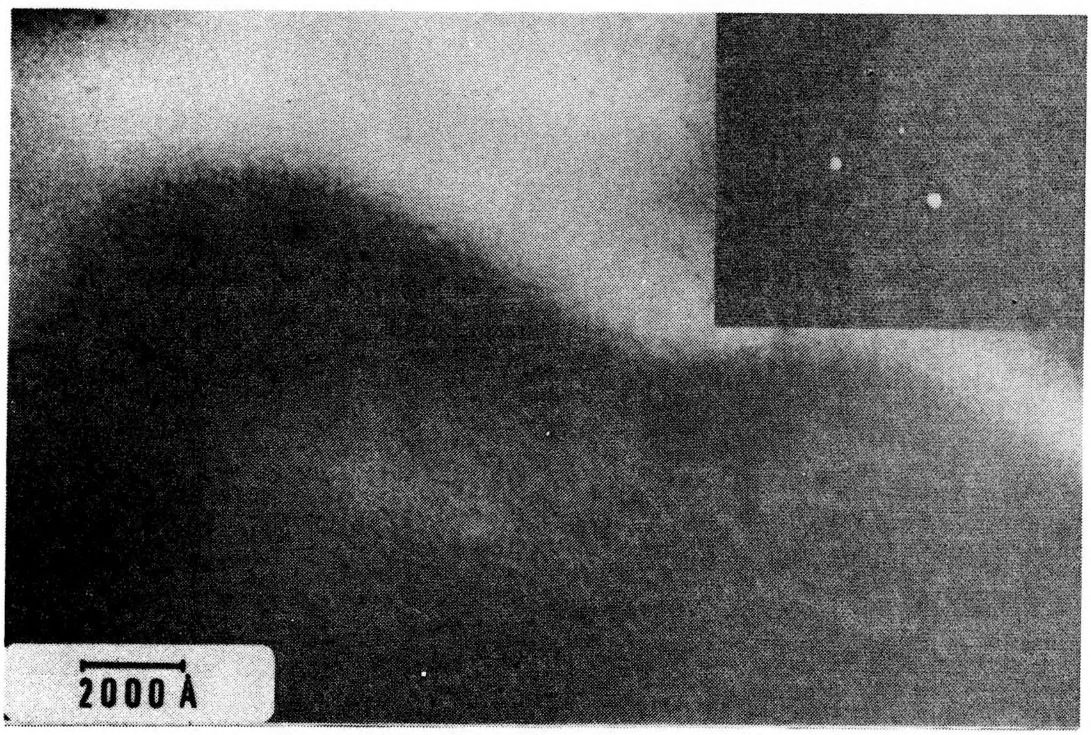


Figure 15. Backscattering spectra of (100) silicon wafers in as-implanted, unimplanted (virgin) and laser anneal (1.5J/cm^{-2}) states. A random spectrum for the virgin crystal is also shown.



(A)



(B)

Figure 16. TEM micrographs of ^{31}P implanted silicon after furnace annealing (900°C/20 minutes) (A) and laser annealing (B).

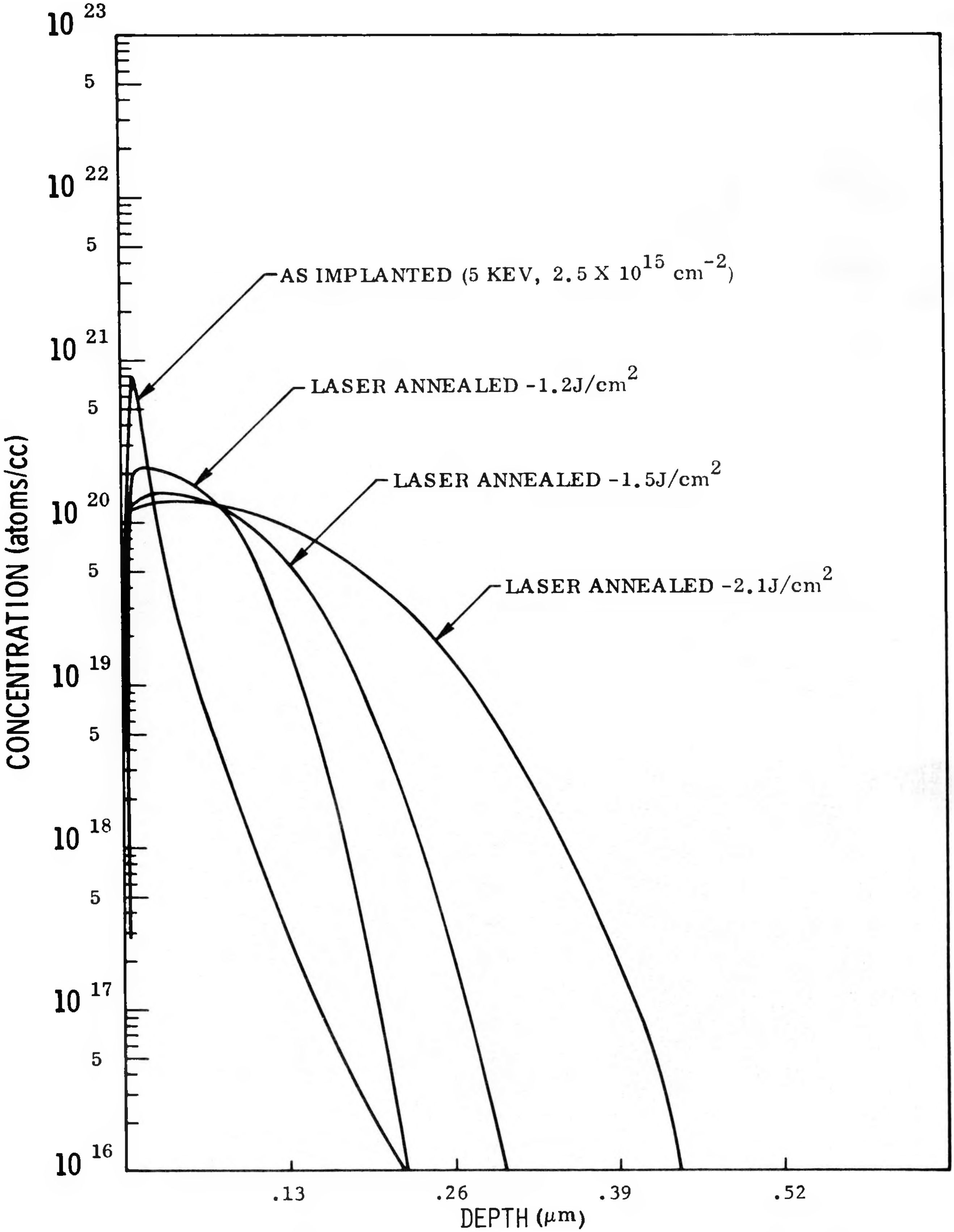


Figure 17. SIMS profiles of 5KeV phosphorus in silicon for as implanted and laser annealed specimens.

3.4 CELL FABRICATION

The obtained TEM, SIMS, and RBS data verified that the selected laser system was capable of annealing the implantation induced damage in silicon, hence yielding an electrically active, defect free, shallow junction device. To further determine optimum fabrication parameters, 2 x 2cm cells were fabricated using a variety of processing conditions. The processing conditions and AM 1 electrical output results are shown in Table 2. All laser annealing was performed with the 30mm diameter fused silica rod with a 90° bend configuration. Ohmic contacting and multilayer anti-reflective coating (MLAR) operations were performed by Applied Solar Energy Corporation (ASEC). Contacts were formed by vacuum deposition of titanium - palladium - silver (front) and vacuum deposition of Al-Ti-Pd-Ag backs. Anti-reflective coating was evaporated TiO_2 and Al_2O_3.

The data presented in Table 2, though limited in quantities by the variable process condition, substantiated the general acceptability of the large spot size laser annealing process.

From the data in Table 2, it is apparent that the contribution of the PEBA formed BSF was insignificant when compared with cells without BSF. When followed by laser pulsing, increased cell output was obtained, leading to the assumption that additional work is required in optimizing the PEBA annealing process. This assumption was further substantiated by SIMS analysis (see Section 3.8).

The data shown in Table 3 was extracted from Table 2, and was ordered by type of cell construction, irrespective of material surface conditions and laser energy densities. It reflects an overview comparison on this initial work on processing parameter determination.

3.5 LASER ANNEALING OF SCALED-UP SIZE CELLS - 2 x 4cm CELLS

Fabrication of scaled-up cell sizes from 2 x 2cm to 2 x 4cm was performed using the two laser energy densities, 1.2 and 1.5J/cm^2, which appeared best suited for annealing at this point of the investigation. The 2 x 4's were annealed with a two-step laser pulse operation, with an approximate 25% overlap to obtain 100% surface irradiation. The cells were fabricated using various processing conditions,

TABLE 2
FUNCTIONAL CELLS - PROCESSING CONDITIONS AND TEST RESULTS

FRONT IMPLANT (2.5×10^{15} cm^{-2})	WAFER SURFACE CONDITION ①	FRONT LASER ENERGY (J/cm^2)	PULSE CONDITION ②	BSF ③	NO. CELLS PROCESSED	Voc RANGE (mV)	Isc RANGE (mA)	CFF RANGE (%)	CONV. EFF. RANGE (%)	Jsc RANGE (mA/cm^2)
10 KEV	PO	FURNACE 875°C/20 min		NONE	2	550,553	126.5,127.5	77,78.6	13.7	31.6,31.9
5 KEV	PO	1.5	SINGLE	NONE	2	553-556	133.6-134.8	74.9-77.1	13.8-14.5	33.4-33.7
5 KEV	FE	1.5	SINGLE	NONE	2	539-546	134-136	72.3-77	13.3-14.1	33.5-34
10 KEV	PO	1.2	SINGLE	NONE	8	543-549	125.7-128	73.9-75.5	12.9-13.1	31.4-32
10 KEV	FE	1.2	SINGLE	NONE	3	530-539	132-133.5	70.5-72.3	12.5-12.8	33-33.4
10 KEV	PO	1.5	SINGLE	NONE	3	549-555	126-127.5	72.8-77.9	12.0-13.6	31.5-31.9
10 KEV	FE	1.5	SINGLE	NONE	2	549-554	131.5-132	74.2-75.8	13.5-13.9	32.9-33
10 KEV	PO	1.5	DOUBLE	NONE	1	554	127	76.5	13.5	31.8
10 KEV	PO	1.5	2 STEP OVERLAP	NONE	1	550	125.5	76.8	13.0	31.4
10 KEV	FE	1.5	2 STEP OVERLAP	NONE	1	545	130	69.0	12.4	32.5
10 KEV	PO	1.9	SINGLE	NONE	3	549-556	125-126.5	75.8-77.1	13.3-13.4	31.2-31.6
10 KEV	FE	1.9	SINGLE	NONE	8	550-555	131-131.5	76.3-77.3	13.8-14.1	32.8-32.9
10 KEV	PO	1.9	DOUBLE	NONE	2	550	125	74.8,76.2	12.8,13.1	31.2-31.6
10 KEV	PO	1.9	2 STEP OVERLAP	NONE	1	549	130.5	72.0	13.1	32.6
5 KEV	PO	1.5	SINGLE	BF_2, PEBA	2	555	132.7,133.6	76.9,77.6	14.2,14.4	33.2,33.4
5 KEV	PO	1.5	SINGLE	BF_2,PEBA + LASER	1	575	139	73.6	14.7	34.8
5 KEV	PO	1.9	SINGLE	BF_2,PEBA + LASER	1	572	136	73.8	14.4	34.0
10 KEV	PO	1.3	SINGLE	BF_2,PEBA	3	545-550	127-128.3	76.7-78.2	13.3-13.8	31.8-32
10 KEV	FE	1.2	SINGLE	^{11}B,BF_2, PEBA	3	534-545	131-132.5	73-77.1	12.6-13.9	32.8-33.1
10 KEV	PO	1.5	SINGLE	BF_2,PEBA	2	540-557	127-127.5	68.9-73.1	11.8-13.0	31.8-31.9
10 KEV	FE	1.5	SINGLE	^{11}B,BF_2, PEBA	2	552	130.5-131	76.7-77.0	13.9-14.0	32.6-32.8
10 KEV	PO	1.5	SINGLE	BF_2,PEBA + LASER	2	560	127.5,128.5	79.3,78.7	14.0,14.2	31.9,32.1
10 KEV	FE	1.5	SINGLE	^{11}B,BF_2, PEBA + LASER	2	565,571	134	74,74.5	14.1,14.2	33.5
10 KEV	PO	1.3	SINGLE	BF_2,PEBA	3	552-556	126-127	77.3-78.3	13.5-13.7	31.5-31.8
10 KEV	FE	1.8	SINGLE	^{11}B,BF_2, PEBA	2	553	131-132	71.4-77.2	12.9-14.0	32.8-33
10 KEV	PO	1.9	SINGLE	BF_2,PEBA + LASER	1	565	126.7	78.1	14.0	31.7
10 KEV	FE	1.8	SINGLE	^{11}B,BF_2, PEBA + LASER	1	560	133.0	72.9	13.0	33.3

LEGEND:
① PO (CHEM POLISHED)
FE (FLASH ETCHED)
② SINGLE PULSE: IRRADIATED ENTIRE 2X2 CM AREA WITH ONE PULSE.
DOUBLE PULSE: SAME AS SINGLE EXCEPT TWO PULSES ON SAME AREA.
2 STEP OVERLAP: TWO PULSES WITH 50% OVERLAP.
③ ^{11}B, BF_2 IMPLANTED AT 25KEV, 5×10^{15} CM^{-2}. PEBA: PULSED ELECTRON BEAM ANNEALED.

TABLE 3

OVERVIEW OUTPUT COMPARISON BY CELL CONSTRUCTION

Type Construction	Size Cells	Qty. Cells	V_{oc} (mV)	I_{sc} (mA)	CFF (%)	η (%)	J_{sc} (mA cm^{-2})
Laser Annealed, No BSF	2 x 2cm	30	530-556	125-136	69.9-77.9	12.4-14.5	31.3-34
Laser Annealed With PEBA BSF	2 x 2cm	20	534-557	126-133.6	68.9-78.2	11.8-14.4	31.5-33.4
Laser Annealed With PEBA & Laser Pulsed BSF	2 x 2cm	8	560-575	126.7-139	72.9-78.7	13.6-14.7	31.7-34.8
Furnace Annealed, No BSF	2 x 2cm	2	550, 553	126.5, 127.5	77, 78.6	13.7	31.6, 31.9
$POCl_3$ Diffused, No BSF	3 in. dia.	48	540-547	1460-1520	71.1-74.6	12.6-13.3	32-33.6

including some with a screened-on and fired aluminum paste to form a back surface field. The processing variations and results of this work are shown in Table 4. Ranking the data by conversion efficiencies shows best results achieved on those cells with a screened-on and fired aluminum back surface field. Table 5 shows the results of the various process configurations, ranked by conversion efficiency groupings.

From the data shown in Table 5, the most promising processes at this phase of the investigation were:

1. Both chem-polished and flash-etched surface wafers.
2. Both 5 and 10 KeV ion implantation levels.
3. Laser anneal at $1.5 J/cm^2$.
4. BSF formed by screen-on and fired aluminum. Laser pulsing over PEBA also reflected favorable results, but a greater in-depth evaluation is necessary which was considered beyond the scope of this contract. The PEBA technique is also in the category of requiring additional development, and will not be further utilized at this time. The aluminum BSF as performed by ASEC is an established process, and was thus used for the balance of the cells requiring a BSF.

3.5.1 Laser Annealed Texture Etched Cells

At the outset of the contract, successful laser annealing of texture etched surfaces was somewhat dubious. This was attributed to the expectation of total destruction of the pyramidal peaks, due to surface melt induced by the pulsed laser energy. The total melt condition, however, had to be verified, which led to the brief work in this area.

Scanning Electron Microscope (SEM) photos, Figures 18 and 19, show representative texture etched surfaces before and after laser annealing. These photos are indeed indicative of the extensive melt induced by laser irradiation on the textured surface. A SIMS profile performed on the phosphorus doped front junction is shown in Figure 20. It appears from the figure that a very deep junction was formed, a condition not desirable for fabrication of high efficiency solar cells. Output conversion efficiencies of the laser annealed texture-etched cells ranged from

TABLE 4

2 x 4 cm CELL PROCESSING VARIATIONS AND RESULTS

WAFER SURFACE CONDITIONS	ION IMPLANTATION LEVELS		SCREEN AL BSF	LASER ENERGY DENSITY (J/cm^2)		QTY CELLS	MEAN VALUES			
	FRONT - ^{31}P	BACK - ^{11}B①/$BF_2$②		FRONT	BACK		Voc (mV)	Isc (mA)	CFF (%)	η (%)
CHEM-POLISHED PO-5	5 KEV, 2.5 x 10^{15}	—	—	1.2	—	5	499	267	72.5	12.2
CHEM-POLISHED PO-5	5 KEV, 2.5 x 10^{15}	—	—	1.5	—	3	538	256	73.0	12.6
CHEM-POLISHED PO-10	10 KEV, 2.5 x 10^{15}	—	—	1.2	—	6	539	253	77.4	13.2
CHEM-POLISHED PO-10	10 KEV, 2.5 x 10^{15}	—	—	1.5	—	3	546	258	78.4	13.8
FLASH-ETCHED FE-5	5 KEV, 2.5 x 10^{15}	—	—	1.2	—	4	474	262	71.9	11.2
FLASH-ETCHED FE-5	5 KEV, 2.5 x 10^{15}	—	—	1.5	—	4	520	265	70.2	12.2
FLASH-ETCHED FE-10	10 KEV, 2.5 x 10^{15}	—	—	1.2	—	2	518	247	76.2	12.1
FLASH-ETCHED FE-10	10 KEV, 2.5 x 10^{15}	—	—	1.5	—	2	536	253	73.9	12.6
TEXTURE ETCHED TE 10	10 KEV, 4 x 10^{15}	—	—	1.2	—	6	463	257	60.7	9.0
TEXTURE ETCHED TE 10	10 KEV, 4 x 10^{15}	—	—	1.5	—	7	512	246	68.3	10.8
WITH BSF:										
CHEM-POLISHED PO5-BSF	5 KEV, 2.5 x 10^{15}	25 KEV, 5 x 10^{15}, ②	—	1.2	PEBA	5	497	265	71.3	11.8
CHEM-POLISHED PO5-BSF	5 KEV, 2.5 x 10^{15}	25 KEV, 5 x 10^{15}, ②	—	1.5	PEBA	4	542	264	76.6	13.8
CHEM-POLISHED PO5-BSF	5 KEV, 2.5 x 10^{15}	25 KEV, 5 x 10^{15}, ②	—	1.5	PEBA + LASER 1.9	4	567	276	73.9	14.5
CHEM-POLISHED PO10-BSF	10 KEV, 2.5 x 10^{15}	25 KEV, 5 x 10^{15}, ②	—	1.2	PEBA	5	541	255	76.6	13.2
CHEM-POLISHED PO10-BSF	10 KEV, 2.5 x 10^{15}	25 KEV, 5 x 10^{15}, ②	—	1.5	PEBA	2	553	251	78.1	13.5
CHEM-POLISHED PO10-BSF	10 KEV, 2.5 x 10^{15}	25 KEV, 5 x 10^{15}, ②	—	1.5	PEBA + LASER 1.9	4	562	259	74.6	13.6
FLASH-ETCHED FE5-BSF	5 KEV, 2.5 x 10^{15}	25 KEV, 5 x 10^{15}, ①+②	—	1.2	PEBA ONLY	3	472	265	68.3	10.7
FLASH-ETCHED FE5-BSF	5 KEV, 2.5 x 10^{15}	25 KEV, 5 x 10^{15}, ①+②	—	1.5	PEBA ONLY	5	529	264	73.3	12.8
FLASH-ETCHED FE5-BSF	5 KEV, 2.5 x 10^{15}	25 KEV, 5 x 10^{15}, ①+②	—	1.5	PEBA + LASER 1.9	3	539	270	73.3	13.3
FLASH-ETCHED FE10-BSF	10 KEV, 2.5 x 10^{15}	25 KEV, 5 x 10^{15}, ①+②	—	1.2	PEBA ONLY	5	541	255	76.6	13.2
FLASH-ETCHED FE10-BSF	10 KEV, 2.5 x 10^{15}	25 KEV, 5 x 10^{15}, ①+②	—	1.5	PEBA ONLY	2	553	251	78.1	13.5
FLASH-ETCHED FE10-BSF	10 KEV, 2.5 x 10^{15}	25 KEV, 5 x 10^{15}, ①+②	—	1.5	PEBA + LASER 1.9	4	563	259	74.6	13.6
TEXTURE ETCHED TE10-BSF	10 KEV, 4 x 10^{15}	25 KEV, 5 x 10^{15}, ②	—	1.2	PEBA ONLY	4	483	247	66.2	9.9
TEXTURE ETCHED TE10-BSF	10 KEV, 4 x 10^{15}	25 KEV, 5 x 10^{15}, ②	—	1.5	PEBA ONLY	2	538	239	76.8	12.4
TEXTURE ETCHED TE10-BSF	10 KEV, 4 x 10^{15}	25 KEV, 5 x 10^{15}, ②	—	1.5	PEBA + LASER 1.9	4	532	242	72.5	11.7
CHEM-POLISHED PO5-BSF	5 KEV, 2.5 x 10^{15}	—	✓	1.5	—	2	583	281	75.1	15.4
CHEM-POLISHED PO10-BSF	10 KEV, 2.5 x 10^{15}	—	✓	1.5	—	5	577	270	76.2	14.8
FLASH-ETCHED FE5-BSF	5 KEV, 2.5 x 10^{15}	—	✓	1.5	—	2	553	272	70.5	13.3
FLASH-ETCHED FE10-BSF	10 KEV, 2.5 x 10^{15}	—	✓	1.5	—	3	574	276	73.0	14.4

TABLE 5

2 x 4cm CELLS RANKED BY CONVERSION EFFICIENCIES

Rank	Conversion Eff. Grouping		Cell Process Configuration
1	15%	15.4	Chem-Pol, 5 KeV, LA* @ 1.5J, AL-BSF
2	14%	14.8	Chem-Pol, 10 KeV, LA @ 1.5J, AL-BSF
		14.5	Chem Pol, 5 KeV, LA @ 1.5J, BSF w/PEBA + Laser
		14.4	Flash Etch, 10 KeV, LA @ 1.5J, AL-BSF
3	13%	13.8	Chem Pol, 10 KeV, LA @ 1.5J, No BSF
		"	Chem Pol, 5 KeV, LA @ 1.5J, BSF w/PEBA only
		13.6	Flash Etch, 10 KeV, LA @ 1.5J, BSF w/PEBA + Laser
		"	Chem Pol, 10 KeV, LA @ 1.5J, BSF w/PEBA + Laser
		13.5	Chem Pol, 10 KeV, LA @ 1.5J, BSF w/PEBA only
		"	Flash Etch, 10 KeV, LA @ 1.5J, BSF w/PEBA only
		13.3	Flash Etch, 5 KeV, LA @ 1.5J, AL-BSF
		"	Flash Etch, 5 KeV, LA @ 1.5J, BSF w/PEBA + Laser
		13.2	Flash Etch, 10 KeV, LA @ 1.2J, BSF w/PEBA only
		"	Chem Pol, 10 KeV, LA @ 1.2J, No BSF
		"	Chem Pol, 10 KeV, LA @ 1.2J, BSF w/PEBA only
4	12%	12.8	Flash Etch, 5 KeV, LA @ 1.5J, BSF w/PEBA only
		12.6	Chem Pol, 5 KeV, LA @ 1.5J, No BSF
		"	Flash Etch, 10 KeV, LA @ 1.5J, No BSF
		12.4	Text Etch, 10 KeV, LA @ 1.5J, No BSF
		12.2	Chem Pol, 5 KeV, LA @ 1.2J, No BSF
		"	Flash Etch, 5 KeV, LA @ 1.5J, No BSF
		12.1	Flash Etch, 10 KeV, LA @ 1.2J, No BSF
5	11%	11.8	Chem Pol, 5 KeV, LA @ 1.2J, BSF w/PEBA only
		11.7	Text. Etch, 10 KeV, LA @ 1.5J, BSF w/PEBA + Laser
		11.2	Flash Etch, 5 KeV, LA @ 1.2J, No BSF

* Laser Annealed

TABLE 5 (Cont.)

2 x 4cm Cells Ranked by Conversion Efficiencies

Rank	Conversion Eff. Grouping		Cell Process Configuration
6	9 & 10%	10.8	Text Etch, 10 KeV, LA @ 1.5J, No BSF
		10.7	Flash Etch, 5 KeV, LA @ 1.2J, BSF w/PEBA
		9.9	Text Etch, 10 KeV, LA @ 1.2J, BSF w/PEBA
		9.0	Text Etch, 10 KeV, LA @ 1.2J, No BSF

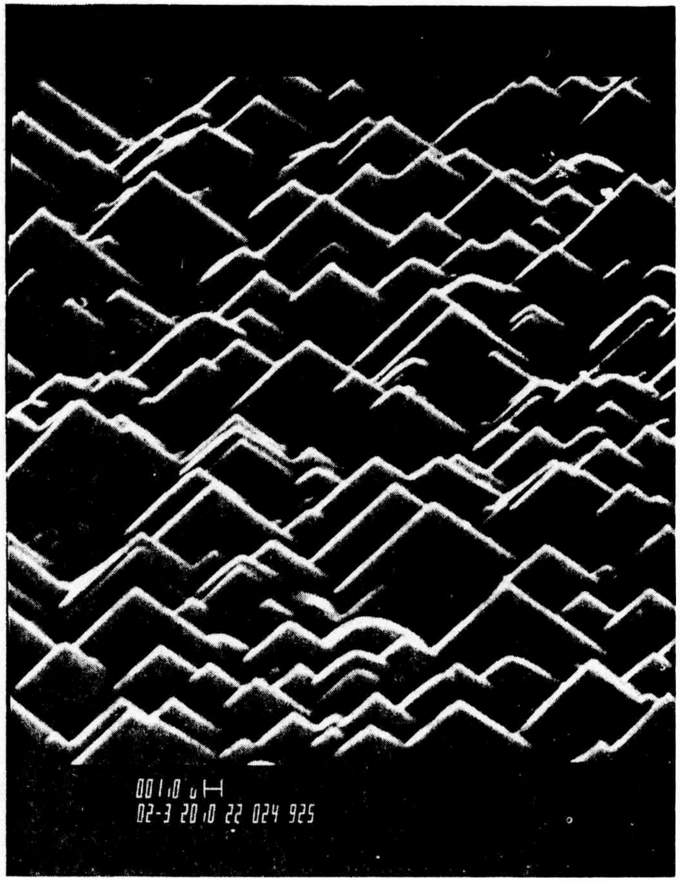


Figure 18

As Implanted, -2000X

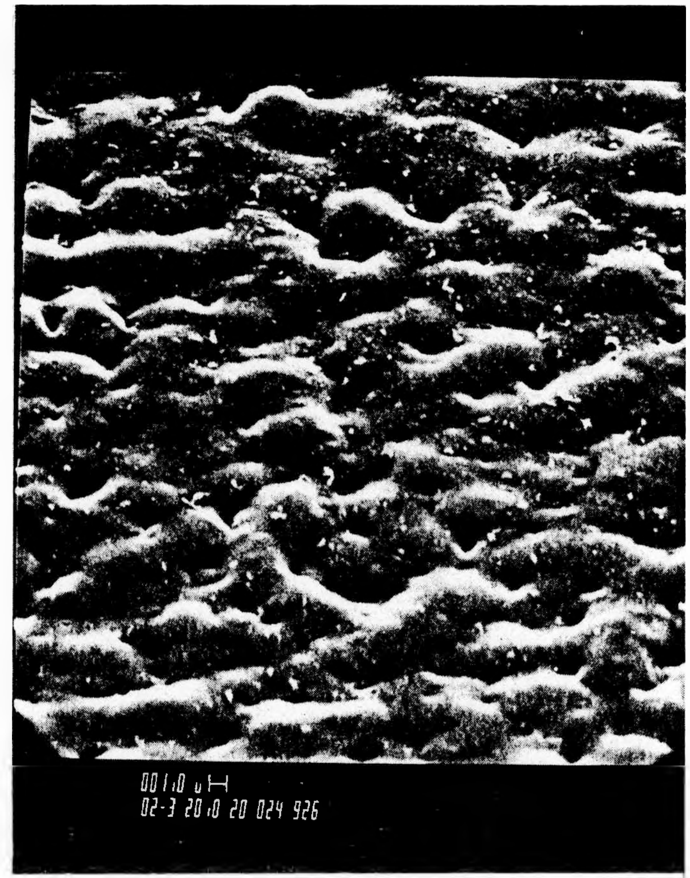


Figure 19

Pulsed Laser Annealed

1.2 J/cm^2 2000X

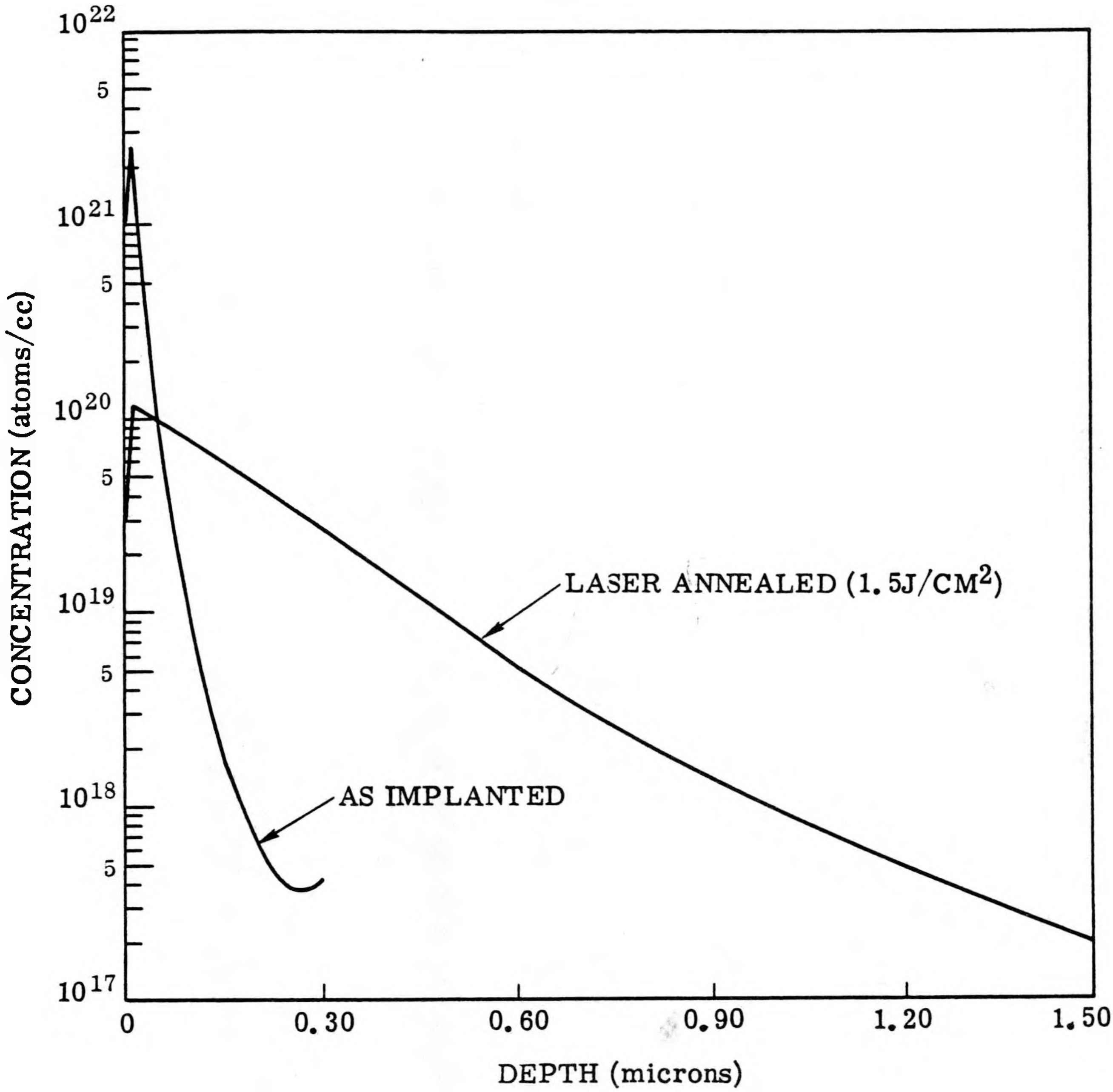


Figure 20. Depth profiles of phosphorus in texture etched silicon for as implanted and laser annealed specimens.

9% to 12.4%, reflecting generally inferior output performances. It was concluded, therefore, that pulsed laser processing is not compatible with texture-etched wafers. Accordingly, no further investigations with texture etched wafers were performed.

3.6 PROCESS VERIFICATION - 2 x 2cm AND 7.62cm DIA. CELLS

During the process verification phase of this study, both small cells (greater than 200 in quantity) and large 3-inch diameter cells (48 in quantity) were fabricated. Process verification on small cells (2 x 2cm) consisted of both single pulse and multi-step overlap pulse annealing. The large 7.62cm diameter cells were the first made using laser annealing under this contract.

3.6.1 Small Cells - 2 x 2cm

Variables in the fabrication of the 2 x 2cm cells for this process verification phase consisted of:

- Chem-polished and flash-etched surfaces.
- 5 and 10 KeV implant energy levels.
- Single and overlap pulse laser annealing.
- With and without screened and fired aluminum for BSF.

Ohmic contacting and MLAR steps were performed as follows:

- P-contact - Evaporated Al (2000Å) - Ti-Pd-Ag (20KÅ)
- Sintered at 400°C/20 min./N_2
- N contact - Evaporated Ti-Pd-Ag (5000Å)
- Entire P & N contacts plated to 5 to 8μm thicknesses
- Multilayer Anti-Reflection coated TiO_2/Al_2O_3
- Sintered at 400°C - 10 min. - N_2

Results of the 2 x 2's are shown in Table 6.

TABLE 6

PERFORMANCE DATA

PROCESS VERIFICATION - SMALL CELLS (2 x 2cm)

Cell (1) Type	BSF	Qty. Cells	V_{oc} (mV)		I_{sc} (mA)		CFF (%)		η (2) (%)	
			Avg.	Range	Avg.	Range	Avg.	Range	Avg.	Range
P05-A	No	16	540	522-550	131	126-133	75	66-79	13.2	11.9-14.3
P05-A	Yes	19	582	574-588	140	133-143	71	64-75	14.4	13.1-15.4
P05-B	No	8	536	520-550	131	127-135	74	70-79	13.0	11.9-14.2
P05-B	Yes	6	577	564-584	138	135-141	72	69-75	14.3	13.7-15.1
P010A	No	11	543	538-546	124	121-131	78	73-82	13.1	11.9-14.3
P010A	Yes	11	580	576-584	131	127-134	73	68-76	13.9	13.0-14.6
P010B	No	5	542	538-546	124	121-126	72	67-78	12.1	11.2-13.2
P010B	Yes	4	580	576-584	132	131-133	72	69-76	13.6	13.0-14.5
P05-1A	No	7	545	542-546	124	123-129	74	71-78	13.3	12.5-14.0
P05-1B	No	4	548	546-548	125	122-128	76	71-78	13.7	12.8-14.2
P010-1A	No	7	549	544-554	123	118-127	76	73-79	13.3	12.7-14.1
P010-1B	No	6	550	544-554	123	118-127	75	72-76	13.0	12.5-13.5
FE5-A	No	11	540	530-544	130	127-133	76	71-79	13.4	11.5-14.1
FE5-A	Yes	14	573	566-578	136	128-139	70	65-73	13.5	12.7-14.4
FE5-B	No	4	543	540-544	131	129-132	73	69-77	12.9	12.2-13.5
FE5-B	Yes	3	574	572-576	134	133-135	71	65-76	13.6	12.5-14.5
FE10-A	No	13	543	528-550	128	123-131	77	72-80	13.3	11.8-14.1
FE10-A	Yes	12	581	576-584	136	133-137	74	71-77	14.6	13.8-15.3
FE10-B	No	4	538	528-546	127	126-128	74	71-78	12.7	11.7-13.5
FE10-B	Yes	4	580	578-580	136	135-137	71	69-73	14.1	13.6-14.6
P05-FA	No	5	544	540-546	131	125-135	78	74-80	13.9	13.0-14.7
P05-FA	Yes	5	570	560-582	132	129-137	75	74-76	14.1	13.0-14.9

(1) I.D. Example: PO or FE 5 or 10 -A-Single Laser Pulse
- PO = Chem-Polished
- FE = Flash Etched
- 5 or 10 = 5 or 10 KeV Implant
- -A-Single Laser Pulse
- -B-Overlap Laser Pulse
- -1A or 1B-New ^{31}P Implants
- -FA-Furnace Annealed 875°C/20 min./N_2

(2) Variations possibly attributed to workmanship as evidenced by some grid line discontinuities and MLAR color non-uniformities reflecting thickness variations.

Laser annealed cells, designated -1A and -1B, were new ^{31}P implants by SPIRE. They were fabricated to determine if there were any significant differences from those originally implanted when it was discovered that the implanter had apparently malfunctioned during the initial batch of 5 KeV implants. Comparison of conversion efficiencies showed no significant differences between the 1st and 2nd implant batches on the limited quantities processed.

The wide variations of conversion efficiencies shown in Table 6 within a particular cell type were believed to be attributed to workmanship aspects in forming the ohmic contacts and anti-reflective coatings. Processing of the 2 x 2's with the fineline ohmic contact pattern was not standard practice with ASEC, which impacted fixturing and handling techniques employed. In order to try to better understand the output variations within a specific type cell, diffusion length measurements were made on high and low output cells. The diffusion length measurements were performed by ASEC on a cross section of fabricated cells to determine if bulk properties were adversely affected due to the different processes used. Specimens included high and low output cells which had been furnace or laser annealed, as well as a diffused junction device. The short circuit current technique was used. Table 7 shows the results of the diffusion length measurements.

Table 7

DIFFUSION LENGTH MEASUREMENTS ON SELECT CELLS

Cell Description	η	Apparent L (μm)	τ(μs)
7.62cm dia. - Furnace Annealed	Low (8-10%)	209	12.8
7.62cm dia. - Furnace Annealed	Moderate (12%)	239	16.7
7.62cm dia. - Diffused Junction	Moderate (12%)	215	13.6
2 x 2cm - Furnace Annealed	Moderate (13%)	260	19.9
2 x 2cm - Furnace Annealed	High (14.7%)	268	21.1
2 x 2cm - Laser Annealed	Low (8.7%)	277	22.6
2 x 2cm - Laser Annealed	High (14.3%)	277	22.6
2 x 2cm - Laser Annealed	Low (8.6%)	326	31.3
2 x 2cm - Laser Annealed	High (14.3%)	260	19.9

From the data, it appears that the apparent diffusion lengths are within the acceptable range for 7-14 Ω-cm material, with the exception of the 326μm value. On this device (FF=53%), both I_{sc} and V_{oc} values were consistent with others in the same batch which displayed acceptable fill factors and conversion eff-ciencies. Examination of the I-V characteristics on the diffusion length measured devices showed low conversion fill factors (60%) on those with low electrical out-put. Indications again strongly point to workmanship factors in applying ohmic contacts.

3.6.2 Large Cells - 7.62cm Dia.

The same general material and process variables were used for the 7.62cm as those used for the 2 x 2cm cells reported in Section 3.6.1, except for laser pulsing and ohmic contact formation. Overlap laser pulsing was used to cover the larger cell area, and no plating of the ohmic contacts was necessary, since ASEC vacuum deposited the silver to a 3 to 5μm thickness.

For these larger cells, an automatic step and repeat controller-positioner was designed and implemented on the laser system. The controller provided the required commands to fire the laser and move the XY positioning table on which the wafer was located under the laser beam. The "programming" in the controller allowed for com-plete wafer irradiation by virtue of 16 laser pulses in a span of 4 minutes, Figure 21. At the completion of the anneal cycle for one wafer, the wafer handler, Figure 22, rotated 45°, bringing the next wafer into a position underneath the homogenizer. In this manner, up to eight wafers could be processed through the controller program sequence.

Performance results for the 7.62cm diameter cells are shown in Table 8. A total of forty-eight (48) wafers were laser irradiated of which thirty (30) were completed into functional cells. Those cells designated FE (for flash etched) were nominally .25mm oversize, which impacted handling survivability, primarily due to fixturing problems for ohmic contacting.

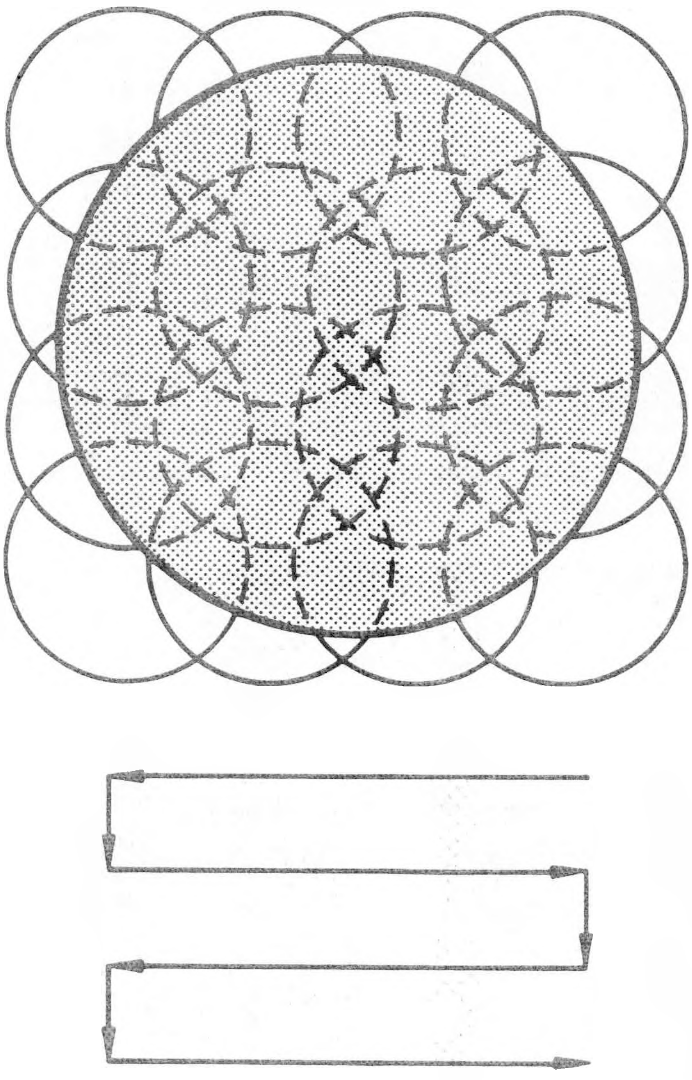


Figure 21. SCAN PATTERN FOR ANNEALING A 3-INCH DIAMETER WAFER

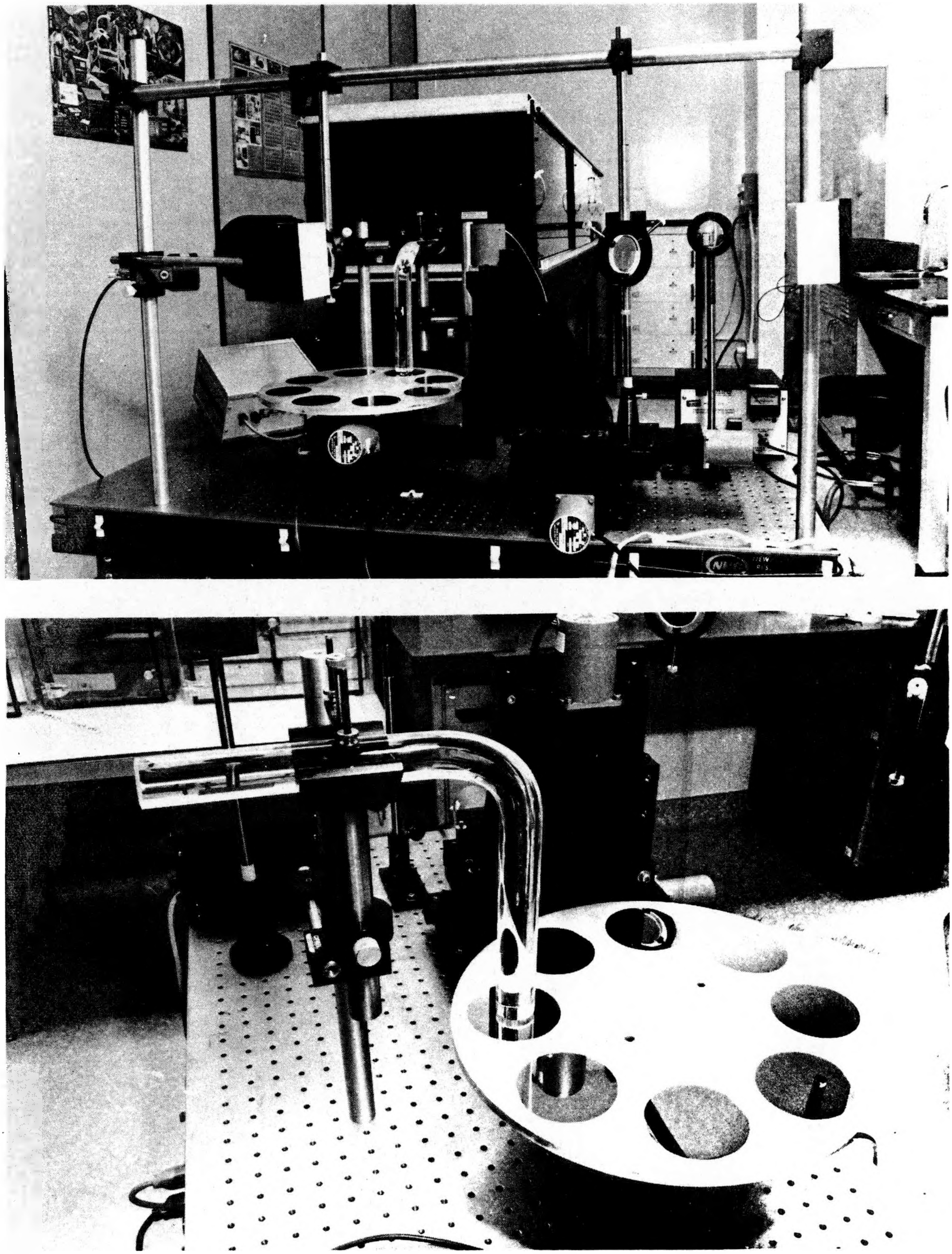


Figure 22. Wafer handler interfaced with linear and rotary stages.

TABLE 8

PERFORMANCE DATA

PROCESS VERIFICATION - LARGE CELLS (3 IN. DIA.)

Cell Type	BSF	Qty. Cells		V_{OC} (mV)		I_{sc} (A)		CFF (%)		η (%)	
		In	Out	Avg.	Range	Avg.	Range	Avg.	Range	Avg.	Range
LASER ANNEALED:											
P05-LA	No	8	6	535	529-545	1.48	1.47-1.50	70.5	67.8-74.6	12.3	11.7-13.4
P05-LA	Yes	4	4	585	580-591	1.58	1.57-1.58	71.0	70-72	14.3	14.2-14.5
P010-LA	No	8	7	548	545-550	1.45	1.44-1.46	73.5	72.2-74.4	12.8	12.6 13.1
P010-LA	Yes	4	3	589	585-592	1.54	1.54-1.55	71.2	71.0-7 5	14.2	14.1-14.3
FE5-LA	No	8	3	535	530-537	1.53	1.53	71.1	70.8-71.3	12.8	12.6-12.9
FE5-LA	Yes	4	2	580	573, 586	1.59	1.58, 1.59	68.1	67.1, 69.1	13.7	13.3, 14.1
FE10-LA	No	8	3	538	535-540	1.49	1.48-1.51	74.1	73.8-74.3	13.0	12.8-13.2
FE10-LA	Yes	4	2	590	590	1.55	1.54, 1.55	70.1	68.8, 71.4	14.0	13.7, 14.3

As a comparison with furnace annealed reference cells, section 3.7.1, it can be seen that the laser annealed cell conversion efficiencies compare favorably. The large laser annealed cells also compare favorably with the 2 x 2's and 2 x 4's, and confirms the general scale-up acceptability of the laser annealing.

3.7 REFERENCE CELLS

3.7.1 Ion Implanted/Furnace Annealed

A group of three inch diameter, ion implanted, furnace annealed cells were fabricated for reference. Annealing was performed at a temperature of 875°C for 20 minutes in a nitrogen atmosphere. These cells consisted of the three (3) wafer surface conditions under evaluation in this investigation, namely, chem-polished, flash-etched, and texture-etched. They were implanted at 5 and 10 KeV levels, and at dosages of 2.5×10^{15} ions/cm^2 (polished and flash-etched) and 4×10^{15} (texture etched) for the front surfaces (^{31}P), and 25 KeV, 5×10^{15} for those with a back surface field ($^{49}BF_2$).

Table 9 shows the electrical characteristics of the fabricated cells. Several cells were broken during fabrication, mainly due to some fixturing problems experienced by ASEC in the ohmic contact vacuum deposition process.

Not included in the table were some furnace annealed 3 inch diameter cells without BSF which had substandard performance characteristics and were considered non-representative. Conversion efficiencies on this "non-representative" batch ranged from 8 to 10.4% for the three surface conditions, chem-polished, flash-etched, and texture etched.

3.7.2 $POCl_3$ Diffused Cells

Also for reference, three (3) inch diameter cells were fabricated by ASEC using their standard $POCl_3$ diffusion process. Cells were made from similar CZ silicon as used for those laser annealed, namely, 10 Ω-cm, 100 , 0.014" thick, chem-polished surfaces, Ti-Pd-Ag contacts and MLAR. Table 10 shows the results of these cells.

Table 10

$POCl_3$ DIFFUSED CELLS (3 IN. DIA.)

Qty. Cells		V_{oc} (mV)	I_{sc} (A)	CFF (%)	η (%)	J_{sc} (mA cm^{-2})
48	Mean :	542.9	1.496	73.4	13.1	32.8
	Range:	540-545	1.46-1.53	71.1-74.6	12.6-13.3	32.-33.6

Table 9

ION IMPLANTED, FURNACE ANNEALED

THREE INCH DIAMETER REFERENCE CELLS

Cell No.	Description	V_{oc} (mV)	I_{sc} (A)	CFF (%)	η (%)
FA- 1	Polished, 5 KeV, No BSF	546	1.45	70.9	12.3
FA- 2	" " " "	545	1.46	73.5	12.8
FA- 3	" " " "	546	1.45	73.4	12.7
FA- 4	" " " "	548	1.46	73.1	12.8
FA- 5	" " " "	546	1.46	72.9	12.7
FA- 6	Polished, 5 KeV, BSF	568	1.53	72.5	13.8
FA- 7	" " "	586	1.53	72.0	13.7
FA- 8	" " "	568	1.53	72.0	13.7
FA- 9	Polished, 10 KeV, No BSF	555	1.44	74.3	13.0
FA-10	" " "	551	1.44	73.8	12.8
FA-11	" " "	548	1.44	74.2	12.8
FA-12	" " "	553	1.46	73.0	12.9
FA-13	" " "	551	1.44	74.3	12.9
FA-14	Polished, 10 KeV, BSF	566	1.52	72.7	13.6
FA-15	" " "	569	1.54	72.9	14.0
FA-16	" " "	569	1.54	72.9	14.0
FA-17	" " "	578	1.50	73.7	14.0
FA-18	" " "	570	1.54	74.4	14.3
FA-19	Flash Etched, 5 KeV, No BSF	540	1.43	73.5	12.4
FA-20	" " " "	540	1.45	73.6	12.6

Table 9 (Cont'd)

Cell No.	Description	V_{oc} (mV)	I_{sc} (A)	CFF (%)	η (%)
FA-21	Flash-Etched, 5 KeV, BSF	576	1.55	72.1	14.1
FA-22	" " " "	576	1.55	72.1	14.1
FA-23	" " " "	576	1.55	72.1	14.1
FA-24	Flash-Etched, 10 KeV, No BSF	547	1.45	73.2	12.7
FA-25	" " " "	546	1.47	72.9	12.8
FA-26	" " " "	548	1.44	73.6	12.7
FA-27	" " " "	549	1.46	73.0	12.8
FA-28	" " " "	549	1.46	73.0	12.8
FA-29	Flash-Etched, 10 KeV, BSF	580	1.55	72.2	14.3
FA-30	" " " "	578	1.52	72.8	14.0
FA-31	Texture Etched, 10 KeV, No BSF	555	1.44	71.6	12.9
FA-32	" " " "	552	1.48	72.2	12.9
FA-33	" " " "	549	1.48	73.1	13.0
FA-34	" " " "	548	1.49	73.3	13.1

3.8 BSF JUNCTION DEPTH PROFILING

As reported in Section 3.4, fabricated 2 x 2cm cells did not exhibit output improvements with an electron beam (EB) annealed back surface field (BSF). Improvement was evident on specimens where EB annealing of the back surface field was followed by laser annealing at $1.5 J/cm^2$. SIMS analysis of sample wafers revealed that the EB annealed profile differs very little from the implanted profile, Figures 23 and 24, probably due to insufficient energy utilized in attempting to EB anneal the BF_2 implant. Some dopant redistribution occurred, but the depth of the p^+ region remained essentially the same.

When the wafers were processed by either laser annealing of the BF_2 implant or by EB annealing followed by laser annealing, the boron profile changed significantly with the result that a ~5500Å deep p^+ region was attained. Typical cell output improvements obtained from EB + laser annealed BSF were 20-30 mV increases in V_{oc}, and up to a 5 mA increase in I_{sc}. This laser over EB processing also yielded the highest conversion efficiency cell at the time, 14.7% AM 1.

In Figures 23 and 24, the profile for the silicon samples that were laser annealed only, were approximately the same depth or deeper than the EB + laser annealed counterparts. This is due to better optical coupling of the laser energy to the silicon surface "amorphized" by the BF_2 implant, as opposed to a surface that has been restored to a single crystal state by EB annealing. The general consensus, nevertheless, is that even a 5500Å deep BSF on a 350μm thick wafer is insufficient for realization of full output improvements that can be attained by a p^+ region. It appears as if the depth of the BSF should be at least 1μm. This would require considerable work, which is not within the scope of this investigation, in optimization of laser parameters to yield such a deep dopant redistribution. Previously developed data on laser parameters for front junction formation is not applicable since these were optimized for the exact opposite, namely, shallow junction conditions.

In Figure 24, a sharp boron peak is shown for the as-implanted specimen. The peak reaches a concentration of 2.5×10^{21} atoms/cm^3 to an approximate depth of 500Å. This is followed by a normal boron implant profile. The sharp peak is a result of a dual implant performed by SPIRE Corporation on the flash etched silicon wafers.

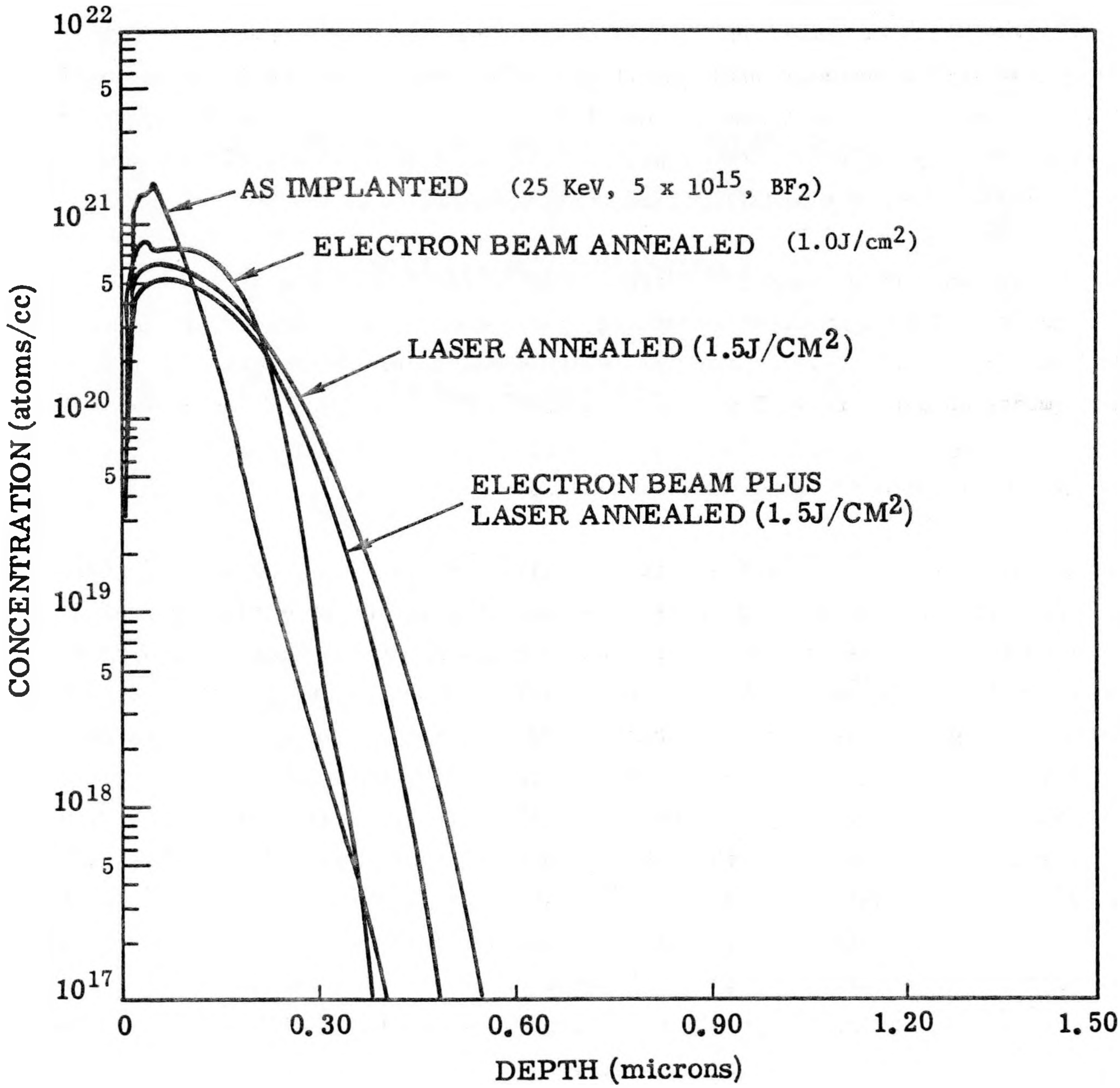


Figure 23. Depth profiles of boron in chem-polished silicon for as implanted, electron beam annealed, laser annealed, and electron beam plus laser annealed specimens.

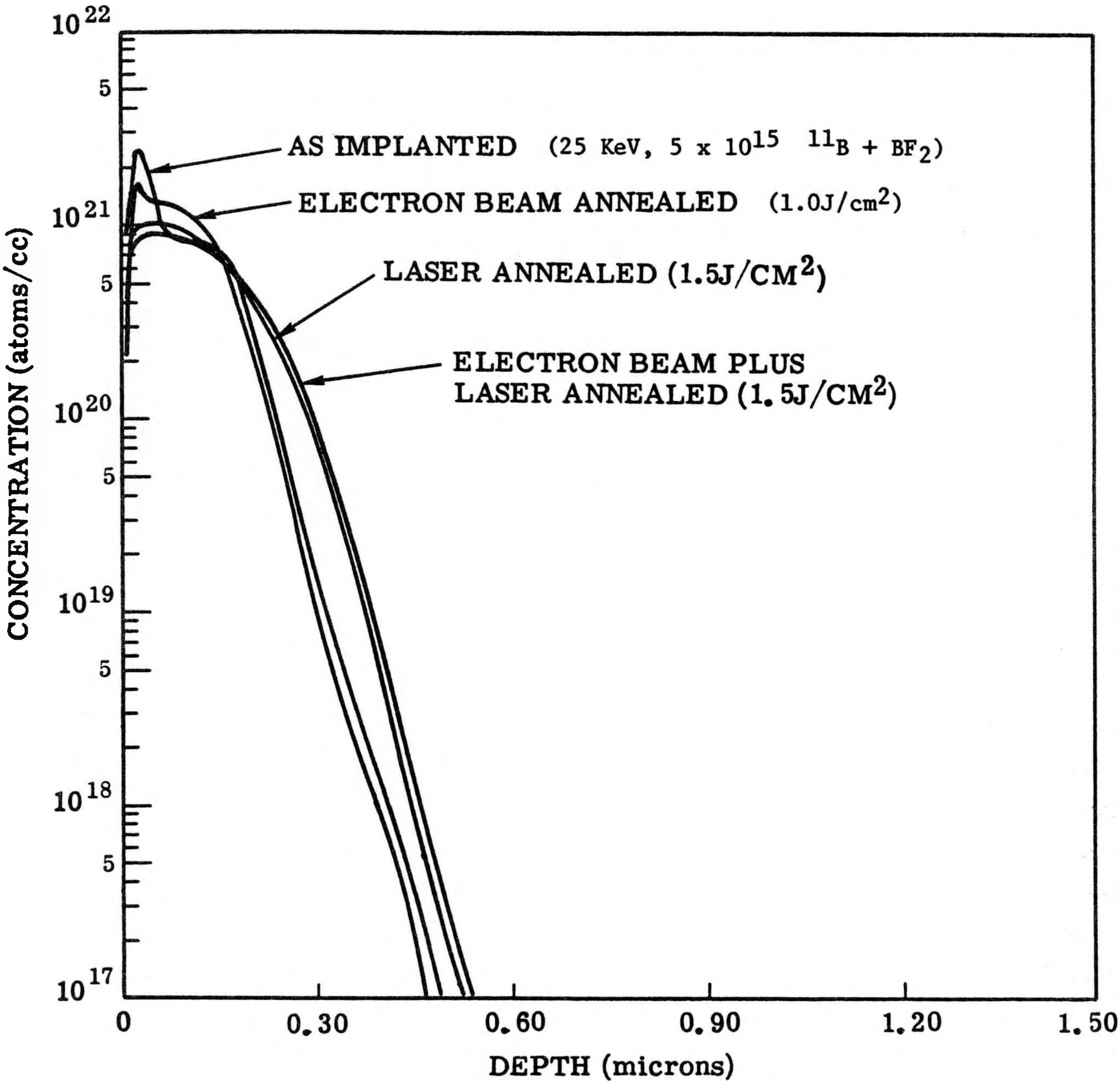


Figure 24. Depth profiles of boron in flash etched silicon for as implanted, electron beam annealed, laser annealed, and electron beam plus laser annealed specimens.

Initially, the wafers were implanted with boron at 25 KeV, 5 x $10^{15}/cm^2$. Evaluations following this implantation by SPIRE revealed that the boron implant did not anneal readily by electron beam annealing. The implantation step was then repeated by SPIRE, but this time using BF_2 at the same energy and dosage levels. Good EB annealing of the BF_2 implant was attained, but as previously indicated, the EB annealed p^+ region was of insufficient depth to bring about cell output improvements.

In view of the good results achieved with the laser pulsing, it was decided to perform some limited experimental work with ^{11}B implants to ascertain whether a deeper p^+ region could be achieved by varying ion implantation and laser annealing parameters.

To this end, silicon wafers were implanted with ^{11}B at 25, 50, and 150 KeV energies, and at 5 x 10^{15} dosage level. Laser annealing was performed at $1.9J/cm^2$, 20nsec pulse settings, and a wavelength mixture of 75% @ 1.06μm and 25% at .53μm. SIMS profiles of as-implanted and annealed specimens in Figures 25-28 revealed considerable boron redistribution of the 25 KeV implant to a depth of approximately .5μm. Some flattening of the 50 KeV profile was observed following laser annealing; however, the profile depth remained essentially the same as the as-implanted profile. This appears to indicate that the melt front induced by $1.9J/cm^2$ laser pulse does not extend beyond .5μm and consequently, anneal energy would have to be increased in order to create a deeper p^+ region and remove the damage induced by implants in the order of 50 KeV and above. Evaluation of the 150 KeV implants proved to be unsuccessful. Laser annealing of the specimens implanted at the 150 KeV level, showed no discernible effects of having been implanted, either visually or electrically. Subsequent SIMS analysis confirmed the absence of "implanted" ^{11}B, Figure 29. The 150 KeV implants were performed with a different (smaller) implanter by SPIRE. In discussions with SPIRE, no obvious reason was derived for this anomaly.

To ascertain the effect of a laser annealed boron BSF, 7.62cm diameter cells were fabricated. Front ^{31}P implantation was carried out at 5 KeV and 10 KeV, 2.5 x 10^{15} $atoms/cm^3$ whereas backside boron implants were, as indicated above, 25 KeV and 50 KeV, 5 x 10^{15} $atoms/cm^2$. Tests on subject cells revealed that the boron BSF unlike the BF_2 BSF did not contribute to cell output improvement. In depth analysis of the problem was not performed, leaving this work for future considerations.

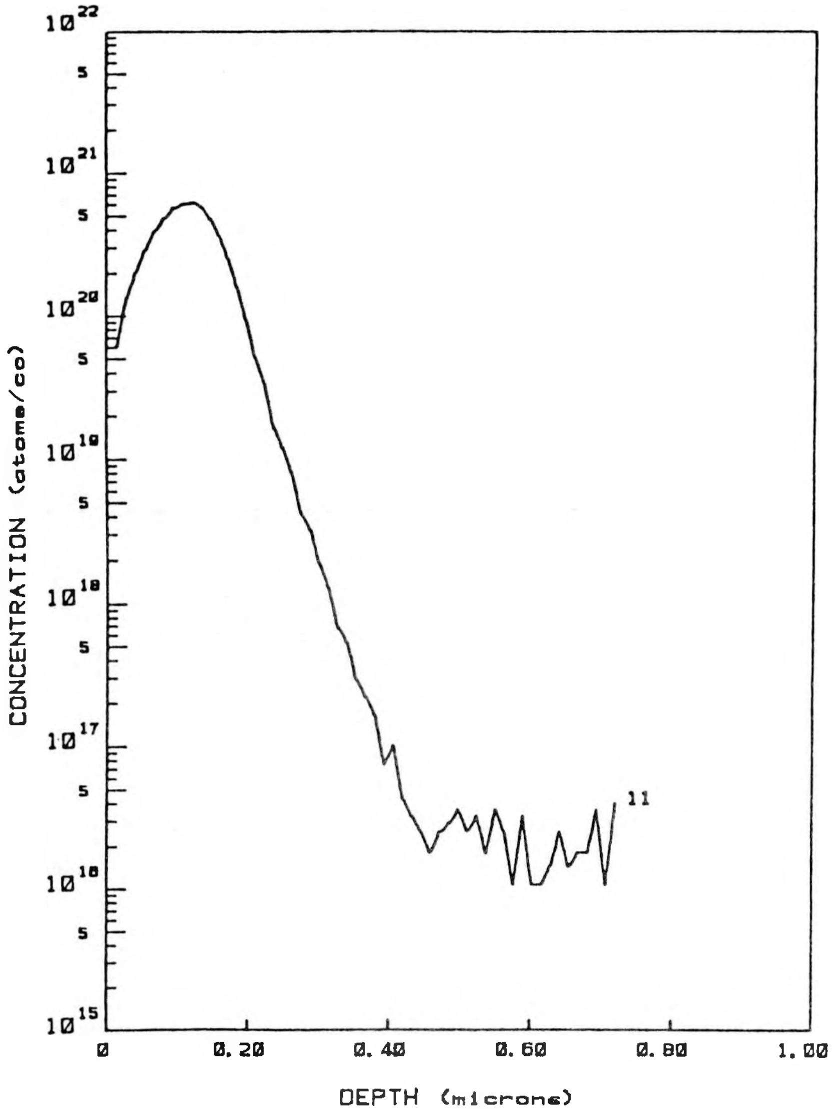


Figure 25. Depth profile of boron in silicon for as-implanted specimen @ 25 KeV/5 x 10^{15}

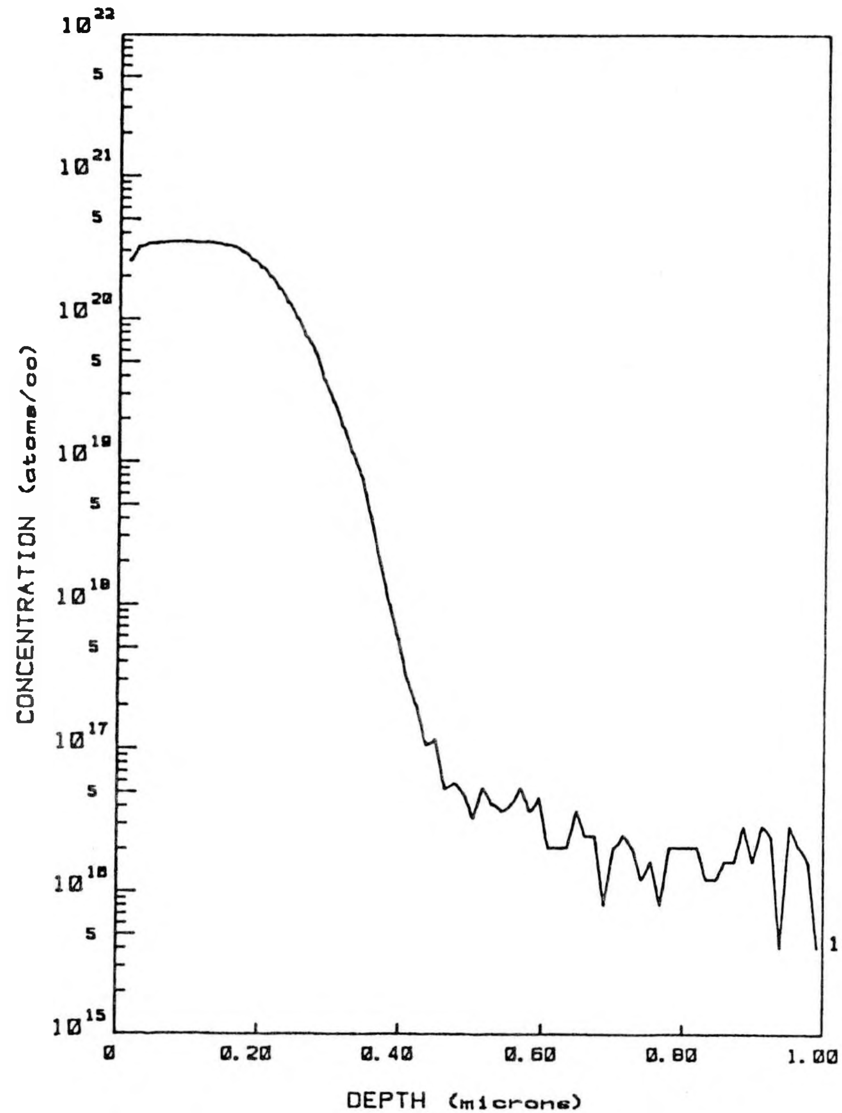


Figure 26. Depth profile of 25 KeV/5 x 10^{15} implanted boron in silicon following laser annealing at 1.9J/cm^2.

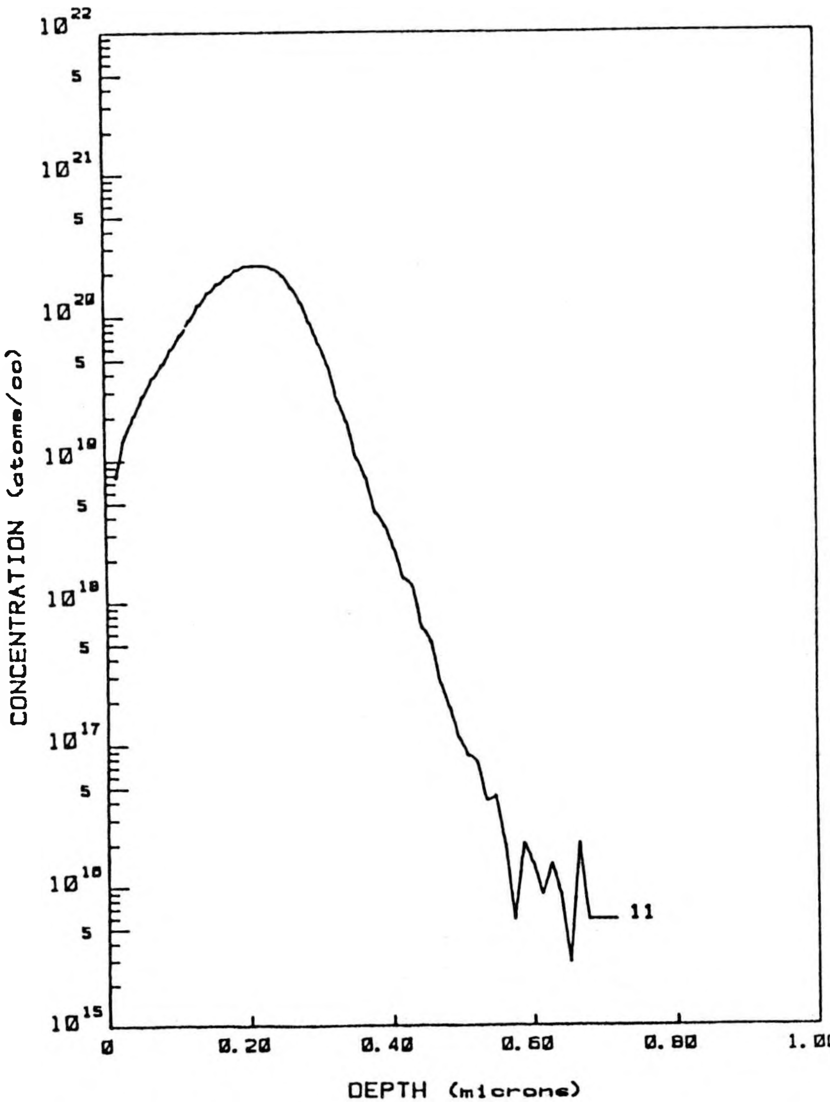


Figure 27. Depth profile of boron in silicon for as-implanted specimen @ 50 KeV/5 x 10^{15}

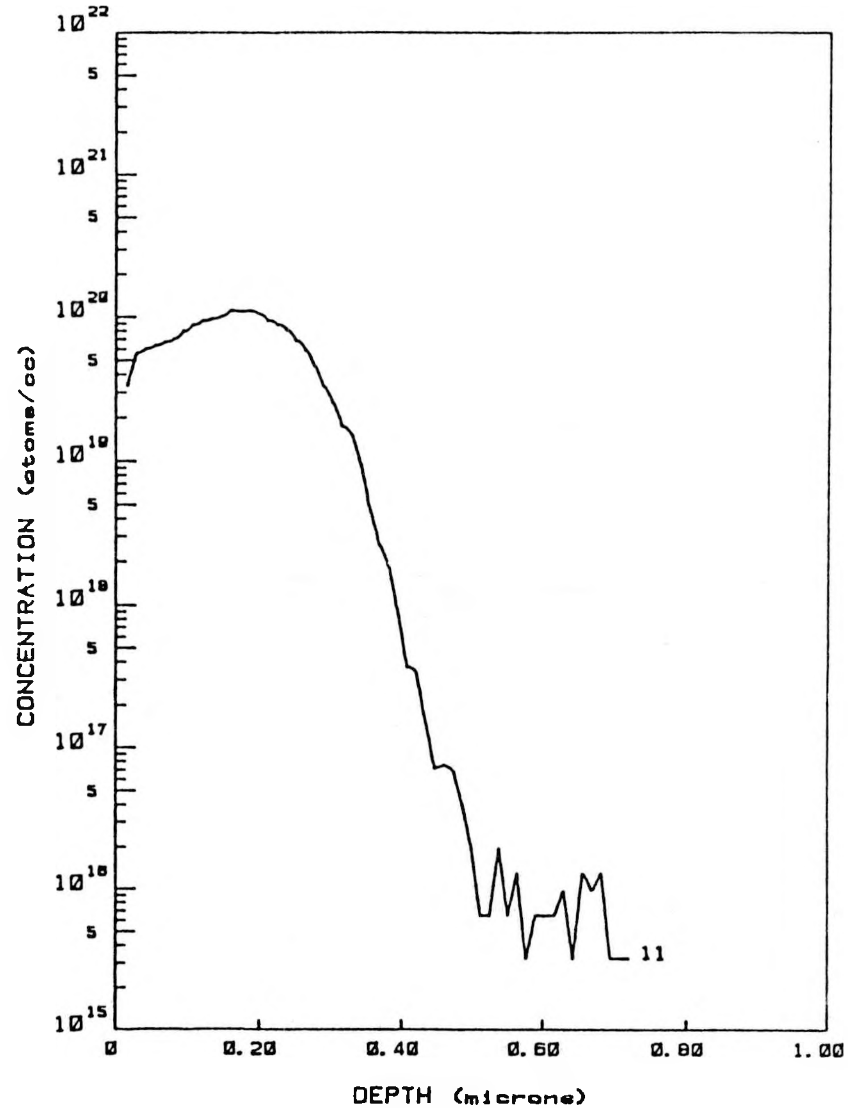


Figure 28. Depth profile of 50 KeV/5 x 10^{15} implanted boron in silicon following laser annealing at 1.9J/cm^2

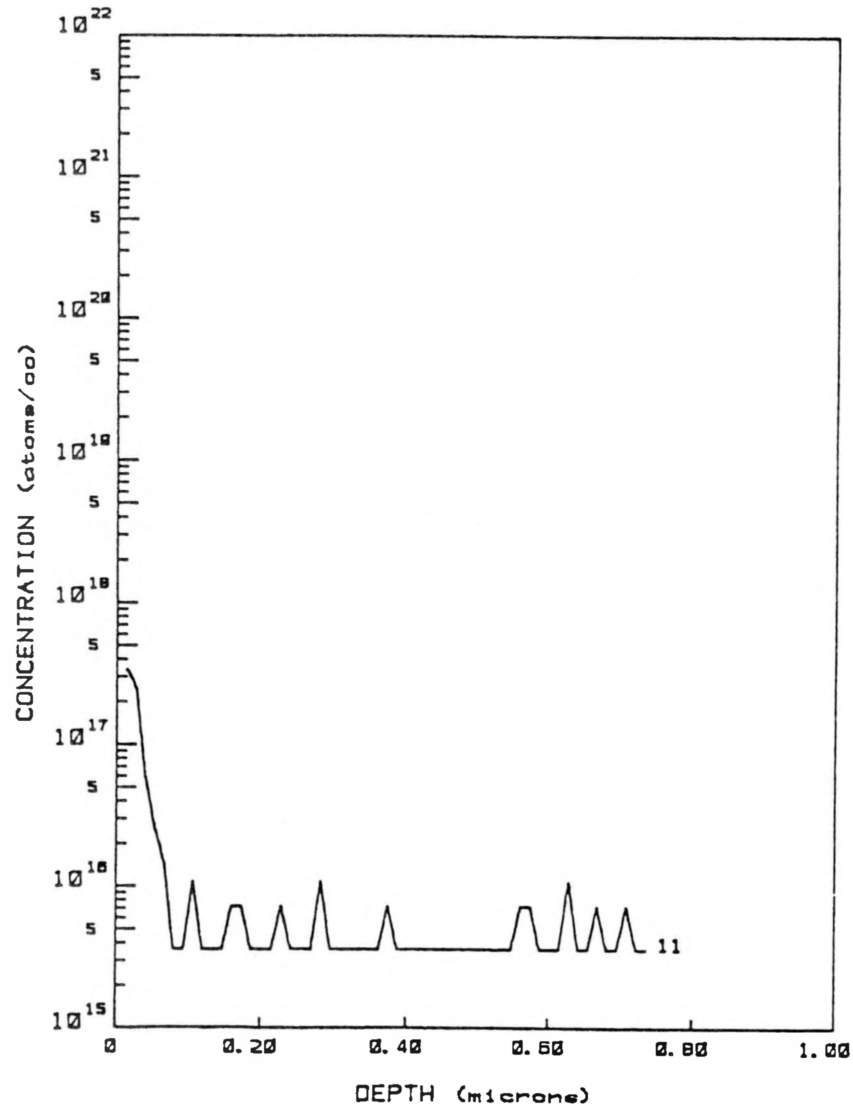


Figure 29. Depth profile of boron in a silicon wafer for a 150 KeV/5 x 10^{15} implant. Absence of typical high concentration boron profile implies either wafer was not implanted, or implanter malfunction.

3.9 FABRICATION OF FINALIZED 7.62cm DIAMETER CELLS

A final batch of 7.62cm diameter cells were fabricated using those parameters found best suited. The junction formation process was narrowed to single ion implantation energy/dosage and laser annealing parameters. The batch of cells fabricated consisted of the following:

	Reg. (No BSF)	With BSF
1) Chem-Polished Surfaces, 7.62cm dia., Ion Implanted/Laser Annealed	40	10
2) Chem-Polished Surfaces, 7.62cm dia., Ion Implanted/Furnace Annealed	40	10
3) Flash Etched Surfaces, 7.62cm dia., Ion Implanted/Laser Annealed	40	10

The process sequence and parameters used for the final cells are detailed as follows:

Starting Material: Chem-Polished and Flash Etched, CZ Silicon, 7.62cm dia., 350μm thick, <100> , 7-14 Ω-cm, p-type (boron)

	Reg. (No BSF)	With BSF
Ion Implantation - Front, ^{31}P	5 KeV, 2.5×10^{15}	Same
Laser Anneal - Front	$1.5 J/cm^2$, 20nsec	Same
or		
Furnace Anneal	$875^{o}C/20$ min./N_2	Same
HF Clean 1:1 Concentration	15 - 30 sec.	Same
CVD N Surface (Front)	N/A	5000Å SiO
Screen Print Back	N/A	Al Paste
Fire	N/A	$800^{o}C/40$ sec.
HCL Clean/Scrub 1:1 Concentration	N/A	20 minute immersion

HF Clean 1:1 Concentration	N/A	30 sec.
P Contact - Evaporate using edge ring mask	Al (2000Å) Ti Pd, Ag (3μm)	Same
Sinter	400°C/10 min./N_2	Same
Photo Resist (KTI) - Front	Yes	Yes
N Contact - Evaporate using edge ring mask	Ti, Pd Ag (4-5μm)	Same
Lift off Resist/Clean	Yes	Yes
MLAR	Yes	Yes
Sinter	400°C/10 min./N_2	Same
Test (AM1)	Yes	Yes

Table 11 shows the results for the final group of 7.62cm diameter cells. The flash-etched surface cells were excluded from the table due to the non-representative nature of the results. Previous three-inch diameter cells as shown in Table 8 were made from the same batch of flash-etched wafers and reflect acceptable output characteristics. This batch of flash-etched cells has conversion efficiencies ranging from 4.4 to 11.6 with a mean of 8.8% for the non-BSF cells. For those with BSF, the output was equally non-representative, 9.0 to 9.8 range, with a mean of 9.3%. An analysis of the causes for the poor quality was not made because of time and funding limitations. This entire batch of flash-etched cells warrants repeat fabrication for conclusive results. However, it is felt that this would be academic, since under better controlled processing conditions, there is reasonable assurance that acceptable cells would result.

Table 11

FINALIZED BATCHES OF 3" DIA. CELLS

Cell Description	Qty. Cells		V_{oc} (mV)	I_{sc} (A)	CFF (%)	(%)	J_{sc} (mA cm^{-2})
Chem-Polished - No BSF Laser Annealed	36	Mean:	535	1.46	68	11.6	34.8
		Range:	522-544	1.42-1.48	66-71	10.9-12.2	
Chem-Polished - BSF Laser Annealed	6	Mean:	595	1.56	70.8	14.3	37.2
		Range:	592-597	1.54-1.56	70-71.7	14.1-14.5	
Chem-Polished - No BSF Furnace Annealed	35	Mean:	550	1.45	72.8	12.7	34.6
		Range:	540-553	1.34-1.47	70.6-77.7	12.0-12.9	
Chem-Polished - BSF Furnace Annealed	9	Mean:	592	1.50	71.2	13.9	35.8
		Range:	587-597	1.47-1.53	70.8-71.8	13.6-14.1	

3.10 HIGH THROUGHPUT LASER SYSTEM

One of the goals of this contract was to develop the criteria and concepts for a production type laser system capable of single pulse annealing of 7.62cm diameter wafers at 1 wafer/second. Based on previously determined requirements of laser energy density needed for annealing ion implanted wafers and optical losses sustained from beam homogenization, it was concluded that a system capable of providing approximately 100 joules of energy in a single 20nsec pulse would satisfy the above stated goal. It was assumed here that at maximum, $1.5 J/cm^2$ is needed to attain good annealing, and that 35% of the available energy would be lost in a homogenizing medium. Since the area of a 7.62cm diameter wafer is $45.6 cm^2$, the required energy on the surface of the wafer is approximately 65 joules. Adding 35% optical losses to this figure results in an approximate 100 joules laser output requirement to yield a 65 joule beam incident on the surface of the wafer. To satisfy this requirement in terms of current state-of-the-art laser technology, a system was proposed by LMSC and discussed with Quantel International, manufacturers of the Nd:Glass system utilized on this contract.

The resultant discussion led to a mutually agreed on system design which would satisfy the 100 joule, 1 PPS (pulse per second) production requirement. A block diagram is depicted in Figure 30. The laser is a Nd:Glass (phosphate glass) system yielding a 45mm beam from each of a group of amplifier stages. Each 45mm amplifier would operate at 100 joules 1/X PPS where X is the number of final amplifier stages in the system. The amplifier stack would fire sequentially with the result that system output would be 1 PPS. Each amplifier, however, would operate at 1/X PPS allowing sufficient cool down time for the amplifier rods. Prior to homogenization, the 45mm beam will be passed through a frequency doubler where approximately 25% of the beam energy is converted to a .53μm wavelength with the remainder at 1.06μm. The beam is expanded to the required size in the homogenizer, and will be capable of single pulse annealing of 7.62cm diameter wafers.

The calculations performed in determining system energy needs for annealing take into account 35% optical losses sustained from the currently utilized laser beam homogenizer. The homogenizer consists of a fused silica rod with a ground input face, polished output face, and a 90° bend in the middle. Additional work in the area of developing improved homogenizers is of paramount importance since reduction in energy losses would allow laser operation at lower energy levels with subsequent

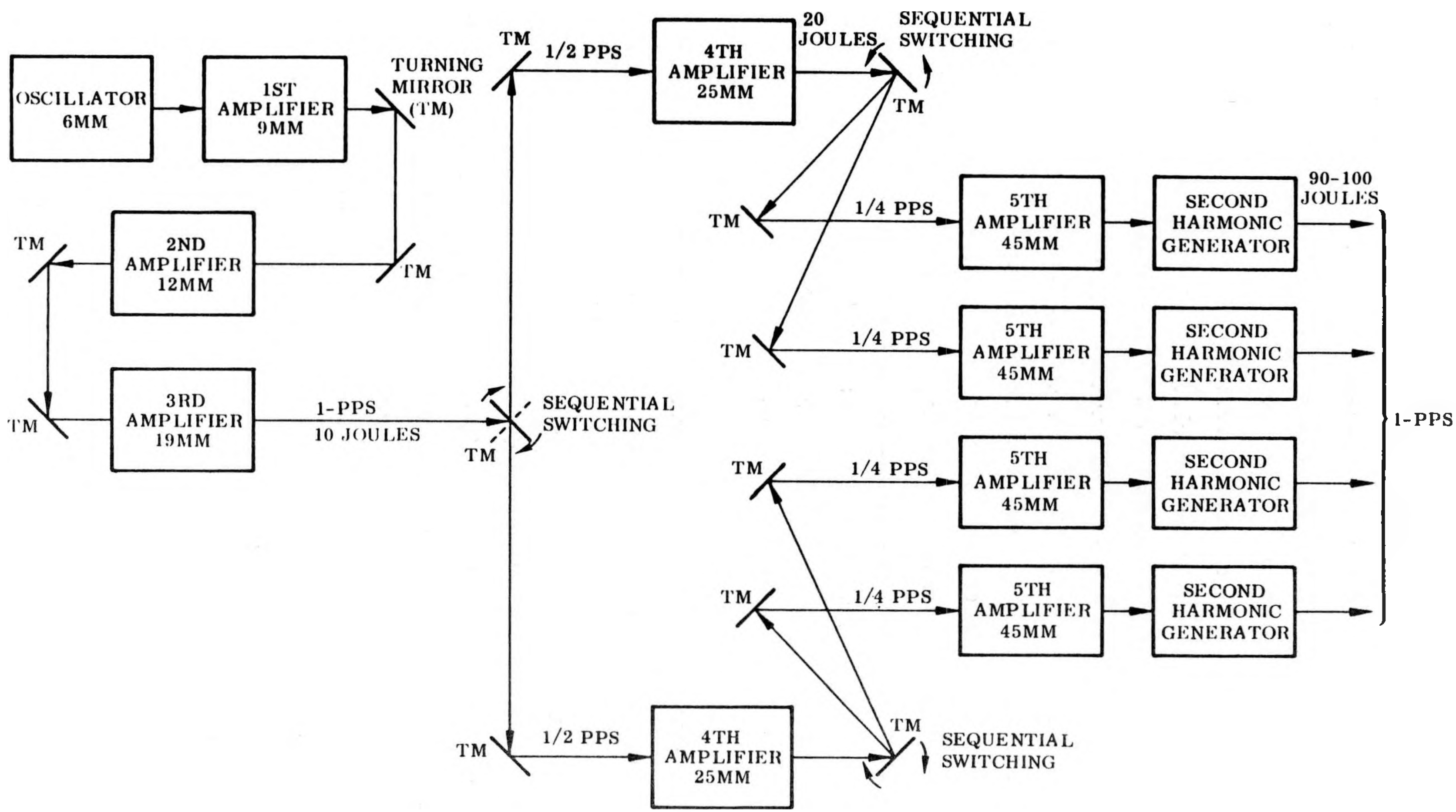


Figure 30. Nd: GLASS LASER FOR 1-PPS APPLICATION - LOW COST SOLAR ARRAY (LSA) PROJECT

decrease in system complexity, number of components (amplifiers), and cost of system operation.

3.11 SAMICS

Solar Array Manufacturing Industry Costing Standards, Format A, was prepared projecting a 1986 laser annealing process with a 1 pulse per second, 7.62cm diameter spot size. The input is included in Appendix A.

SECTION 4

CONCLUSIONS

4.1 Large spot size, single pulse laser annealing yields active, defect free, shallow junction silicon substrates from which high efficiency solar cells can be fabricated. A laser energy density of $1.5 J/cm^2$ was found to be best suited.

4.2 Laser annealed solar cells yield conversion efficiencies as good or better than those furnace annealed. However, laser annealing would best serve the low cost objectives of the LSA Project through its excellent high throughput potential.

4.3 Five (5) KeV ion implanted/laser annealed solar cells appear to exhibit increased conversion efficiency coupled with shallower junction in comparison to 10 KeV implanted cells.

4.4 Low cost flash etching for saw damage removal on the silicon substrates is compatible with laser annealing in the fabrication of high efficiency solar cells. However, chem-polished surfaces are preferred provided the ASEC process can be scaled-up to a high throughput status.

4.5 Texture etched silicon surfaces are not compatible with pulsed laser annealing processing.

4.6 Ion implantation/pulse annealing parameters for a Back Surface Field formation require further development for optimized performance.

4.7 Screened and fired aluminum paste for a Back Surface Field formation yields excellent performance in combination with front implant/laser annealed devices.

4.8 A high throughput pulsed laser system to accommodate single pulse annealing of three (3) inch diameter wafers at a rate of one (1) per second appears feasible.

SECTION 5

RECOMMENDATIONS

5.1 It is recommended that additional work be performed to assess the best suited process for back surface field formation for the LSA program. Processes for consideration include: (1) ion implanted ^{11}B or BF_2 followed by PEBA or laser pulse; (2) screened-on and fired aluminum in conjunction with laser annealed front junctions.

5.2 Initiate the development for a basic high throughput laser system to determine proof of operation.

SECTION 6

NEW TECHNOLOGY

6.1 Title: Large Spot Size (30 mm dia.) Pulsed Laser Annealing of Ion Implanted Silicon Wafers

Innovators: Jerry S. Katzeff and Mike Lopez

Reference Reports:

Monthly Progress, October 1980, p. 1
Quarterly Report No. 2, October 1980, pp. iii, 1, 9, 13, 15
Monthly Progress, November 1980, pp. 1, 2
Monthly Progress, January 1981, pp. 1, 2, 4
Quarterly Report No. 3, January 1981, pp. iii, 1, 2, 3

6.2 Title: High Throughput Pulsed Laser Annealing System for Three Inch Diameter Silicon Wafers.

Innovator: Jerry S. Katzeff

Reference Reports:

Monthly Progress, November 1980, pp. 1, 2, 6
Quarterly Report No. 3, January 1981, pp. iii, 1, 2, 19, 21

REFERENCES

[1] M. Lopez, J. S. Katzeff, et al, Phase 2, Automated Array Assembly, Task IV, Low Cost Solar Array Project, Final Report 1978, Lockheed Missiles and Space Company, Inc., JPL Document 954898-78-4.

[2] A Device for Laser Beam Diffusion and Homogenization/A. G. Cullis, H. C. Webber and P. Bailey, Royal Signals and Radar Establishment, England. J. Phys. E:Sci. Instrum., Vol. 12, 1979. Printed in Great Britain.

APPENDIX A

SOLAR ARRAY MANUFACTURING INDUSTRY COSTING STANDARDS
(SAMICS)

FORMAT A

SOLAR ARRAY MANUFACTURING INDUSTRY COSTING STANDARDS

FORMAT A

PROCESS DESCRIPTION

JET PROPULSION LABORATORY
California Institute of Technology
4800 Oak Grove Dr. / Pasadena, Calif. 91103

A1 Process Referent LASANNEAL

A2 Description (Optional) Laser Anneal Face of Wafer

PART 1 — PRODUCT DESCRIPTION

A3 Product Referent L.A. Wafer

A4 Name or Description Laser Annealed 3-inch Diameter Wafer

A5 Units Of Measure Wafers

PART 2 — PROCESS CHARACTERISTICS

A6	Output Rate	50	Units (given on line A5) Per Operating Minute
A7	Average Time at Station	.33	Calendar Minutes
A8	Process Usage Time Fraction	.976	Average Number of Operating Minutes Per Minute

PART 3 — EQUIPMENT COST FACTORS

A9	Component Referent			
A10	Base Price Year For Purchase Price	1981		
A11	Purchase Price ($ Per Component)	$700,000		
A12	Anticipated Useful Life (Years)	7		
A13	Salvage Value ($ Per Component)	$300,000		
A14	Cost of Removal & Installation ($/Component)	$ 10,000		

NOTE: See also Appendix notes to Laser Anneal for details.

JPL 3037-S 11/77

Format A: Process Description (Continued)

A14 Process Referent (From Page 1) LASANNEAL

PART 4 — DIRECT REQUIREMENTS PER MACHINE

A16 Catalog Number	A17 Requirement Description	A18 Amount Required Per Machine	A19 Units
A-2064D	Mfg. Space	1000	Sq Ft
B-3704D	Electronics Technician Automated Processes	.25 persons/shift	Person Years

PART 5 — DIRECT REQUIREMENTS PER BATCH (A continuous process has a "batch" of one unit)

A20 Catalog Number	A21 Requirement Description	A22 Amount Required Per Batch	A23 Units
C-1016B	Tap Water	10	Gal/Min
C-1032B	Electricity	.33	KW hr/min
	Flash Lamps	.20	dollars/min

PART 6 — INTRA-INDUSTRY PRODUCT(S) REQUIRED

A24 Product Reference	A25 Product Name	A26 Yield Factor (Usable Output/Input)	A27 Units
I.I. Wafer	Ion Implanted Wafer	*99.2%	L.A. Wafer/I.I. Wafer

Prepared by R. J. Casey Date 22 June 1981

*No inspection is planned at completion of this operation. Figure represents average yield for each of seven process steps with final inspection yield of 95%.

REVERSE SIDE JPL 3037-S 11/77

APPENDIX TO FORMAT A - LASER ANNEAL

Prepared by R. J. Casey
LMSC
March 27, 1981

EQUIPMENT DESCRIPTION

Quantel Nd:Glass Laser

This will be a specially designed unit, dedicated to this operation.

Laser energy density of 1.5 joules/cm^2 is required to attain annealing of ion implanted silicon wafers. This translates to an energy of 68 joules for single pulse annealing of a three inch diameter wafer. It is necessary to incorporate a beam homogenizer to effect uniform distribution of the energy over the face of the wafer. The homogenizer energy loss is approximately 33 percent, requiring an energy of approximately 100 joules to accomplish the annealing of a wafer. A Q-switched Nd:Glass laser capable of operating at this energy level with a pulse repetition rate of one pulse per second has a conversion efficiency of approximately .5%.

Power Requirements

With the homogenizer 100 joules are required to anneal a 3-inch diameter wafer. At .5% conversion efficiency, the laser requires 100/.005 = 20,000 joules = 5.556 watt hrs/wafer.

Wafer Transport

The assumption is made that wafers will be carried to the laser annealing work station on a belt conveyor, in single file, uniformly but not precisely spaced. This assumption is consistent with plans defined in previous LMSC work under Contract No. 954898. The four parallel second harmonic generators shown in the block diagram of the laser system (Figure 1) represent the four exit points for the sequentially generated laser beams, pulsed at one second intervals. A "pick and place" robot, fitted with four in-line vacuum chucks at the end of the arm will be used to pick off four wafers simultaneously from the end of the conveyor belt and transfer them to similarly grouped vacuum chucks on a turntable which indexes the wafers under the laser beam exit points. The table remains stationary for four seconds. During this period the laser beam is pulsed four times, once for each of the four wafers on the turntable. It is then indexed again, bringing four new wafers into position and placing the finished wafers into place for the transfer by a second "pick and place" robot to a take-off conveyor. Precise placement of the wafers on the turntable for processing is achieved by a secondary slide adjacent to the table which pushes the vacuum chucked wafers into final location. The turntable has four index stations holding four steps; load, align, laser anneal and unload. Index occurs at intervals of slightly less than 5 seconds, 4 seconds at rest for completion of the operation steps plus just under one second for table rotation. Throughput rate is 50 wafers per minute.

A-6 Output Rate - 50 wafers/minute

Determined by pulse rate of Quantel Laser at 1 pulse per second and by time required for turntable index after each four pulses. See also equipment description.

A-7 Average Time at Station = .33 minute

Wafers loaded to turntable remain through four indexes at approximately 5 seconds each = 20 seconds or .33 minute.

A-8 Process Usage Time Fraction = .976

Arbitrary assumption of 4 hours per week for maintenance. Plant operation taken as 24 hours/day x 7 days/week = 168 hours less 4 hours downtime = 164 hours. 164 ÷ 168 = .976

A-9	Component Referent	N/A
A-10	Base Price Year for Purchase Price	1981
A-11	Purchase Price Manufacturers Estimate	$700,000
A-12	Anticipated Useful Life (Years) From 5101-33 Interim Price Estimation Guidelines, p. 21	7
A-13	Salvage Value Arbitrary value based on high capability for refurbishment and update of equipment	$300,000
A-14	Cost of Removal & Installation Arbitrary Estimate. Requires only electrical and cooling water hookups.	$10,000

LASER ANNEAL FORMAT A PART 4

DIRECT REQUIREMENTS PER MACHINE

A-16 Catalog Number	A-17 Requirements Description	A-18 AMT Req'd. per Machine	A-19 Units
A-2064 D	Mfg. Space	1000 Laser unit and power supply = 30 x 16 ft. with allowance for machine access - use 40 ft. x 25' = 1000 ft^2	Sq Ft
B-3704 D	Electronics Technician Automated Processes	1.0 Assumes one operator tending 4 machines .25 operator x 4 crews = 1.0 operator	Person/ Years

LASER ANNEAL FORMAT A PART 4

DIRECT REQUIREMENTS PER BATCH

A-20 Catalog Number	A-21 Requirement Description	A-22 AMT Req'd. per Batch	A-23 Units
C 1016 B	Tap Water	10 per equipment mfr'r.	Gal/Min
C 1032 B	Electricity	.2778 5.556 W hr/Wafer (see equip. description) @ 50 wafers/min = 277.8 W hr/min or .2778 KW hr/min	KW hr/ min
?	Flash Lamps	1968 (see attached explanation)	$/wk

EXPLANATION OF A-22 FOR FLASH LAMP REQUIREMENTS

The block diagram for the Nd:Glass Laser (Figure A1) shows the various stages in the amplification of the laser beam. The numbers of flash lamps in each stage and their frequency of operation are defined in the following chart.

Stage	Lamps & Arrangement	Flash Interval (Seconds) 2	4	8
Oscillator	4 lamps in two banks of 2	2 2		
1st Amplifier	4 lamps in two banks of 2	2 2		
2nd Amplifier	6 lamps in two banks of 3	3 3		
3rd Amplifier	6 lamps in two banks of 3	3 3		
4th Amplifier #1	8 lamps in two banks of 4		4 4	
4th Amplifier #2	8 lamps in two banks of 4		4 4	
5th Amplifier #1	12 lamps in two banks of 6			6 6
" " #2	12 lamps in two banks of 6			6 6
" " #3	12 lamps in two banks of 6			6 6
" " #4	12 lamps in two banks of 6			6 6
	TOTAL	20	16	48
	x Flashes/Minute @ 50 Pulses/min.	25	12.5	6.25
	Total Flashes/min. =	500	200	300

Total Flashes/minute - All lamps = 1000

Total Flashes/hour - All lamps = 60,000

Total Flashes/164 hr. wk. = 9,840,000

÷ Estimated 300,000 Flash Lamp Life = 32.8 lamps/wk.

x Estimated $60.00/lamp = $1968/wk.

Lamp Replacement Cost

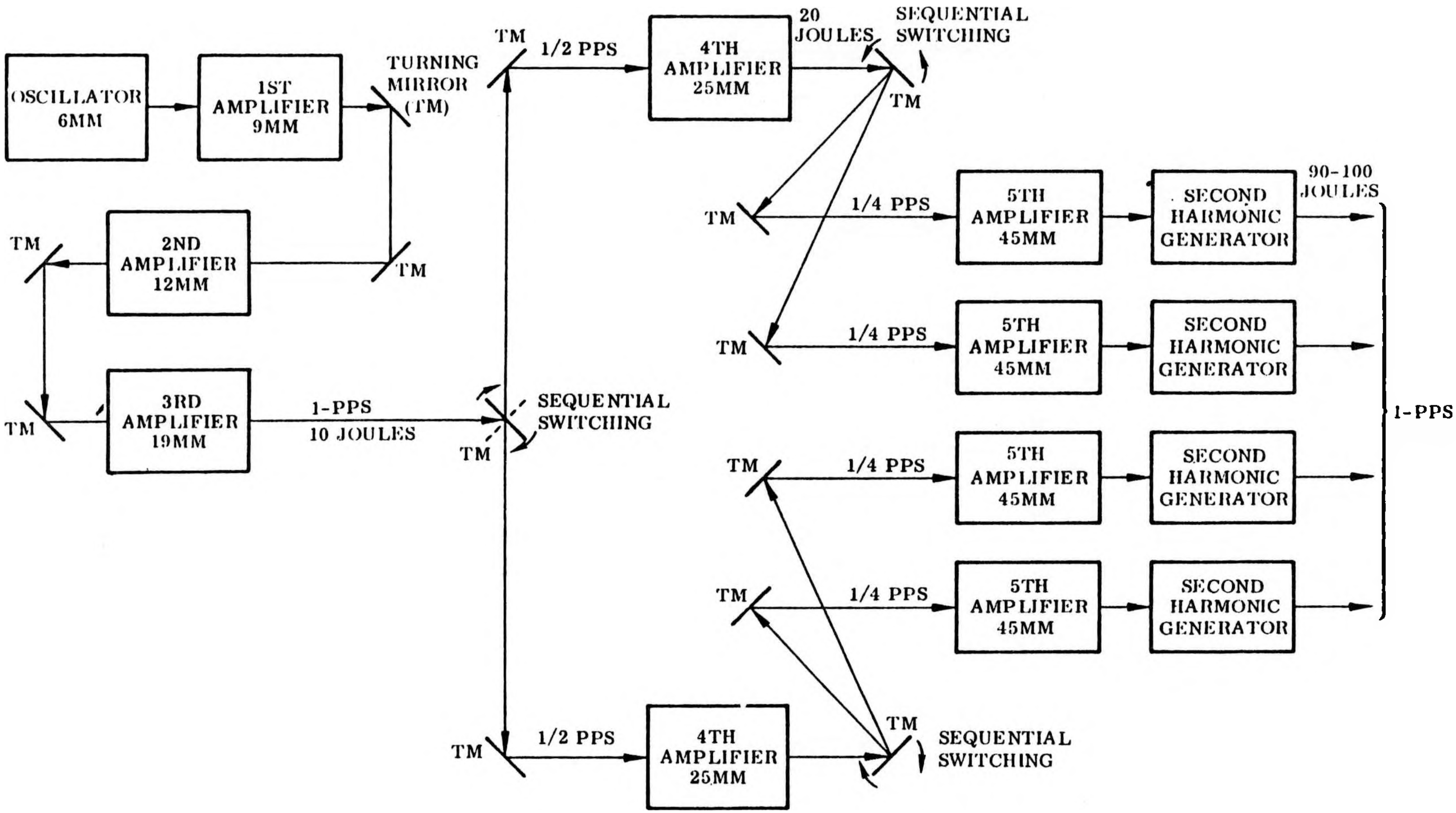


Figure A1. Nd: GLASS LASER FOR 1-PPS APPLICATION - LOW COST SOLAR ARRAY (LSA) PROJECT

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