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

Quarterly Report No. 3

By
J. S. Katzeff
M. Lopez

January 1981

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

Lockheed Missiles & Space Company, Inc.
Sunnyvale, California

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Prepared By:

J. S. Katzeff
Principal Investigator

M. Lopez
Project Leader

LOCKHEED MISSILES & SPACE COMPANY, INC.
1111 Lockheed Way
Sunnyvale, CA 94086

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ABSTRACT

This report describes the third quarter results on a contract to evaluate the merits of large spot size pulsed laser annealing of ion implanted silicon wafers for junction formation of solar cells.

Three inch diameter cells were fabricated for reference by furnace annealing of the ion implanted wafers. Conversion efficiencies on these cells ranged from 12.3% to 14.3%, with and without a BSF.

Scaled-up size cells, from 2 x 2cm to 2 x 4cm, were fabricated using a two-step 25% overlap pulsed laser annealing process. Conversion efficiencies up to 15.4% were achieved.

Pulsed laser annealing of textured surface wafers proved unacceptable based on the subpar electrical performances of fabricated 2 x 2cm and 2 x 4cm cells. Further laser annealing work using textured surfaces has been discontinued.

SIMS profiling of ^{11}B and/or $^{49}BF_2$ ion implanted species for back surface field followed by pulse annealing, both by electron beam and laser, revealed that additional work is required for optimization.

The process verification phase of the contract was initiated for small (2 x 2cm) and large (3 in. dia.) cells using the surviving processing candidates showing best promise.

A high throughput laser system was conceptualized which will accommodate three (3) inch diameter wafers at a rate of one per second.

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SUMMARY

Three inch diameter cells were fabricated by furnace annealing for reference during this reporting period. Cells, furnace annealed at 875°C for 20 minutes in a nitrogen atmosphere, consisted of the three surface conditions, i.e., chem-polished, flash-etched, and texture-etched, and were both with and without BSF. The conversion efficiencies of representative cells ranged from 12.3% to 14.3%, with and without a BSF.

Scaled-up size cells, from 2 x 2cm to 2 x 4cm, were laser annealed using a two-step 25% overlap pulsing mode, and fabricated into functional devices. Cells with a screened on and fired aluminum paste for a Back Surface Field yielded the highest conversion efficiencies, up to 15.4%.

Pulsed laser annealing of textured surface wafers resulted in the expected subpar electrical performances due to extensive surface melting and destruction of the pyramidal peaks. Continuing work on this contract will be performed with chem-polished and flash-etched surface wafers only.

SIMS profiling of 2 x 2cm samples fabricated and reported in the previous report was performed to determine distribution of the dopant used for the BSF formation. It was found that there were little depth differences between the as-implanted and Pulsed Electron Beam Annealed (PEBA) profiles. Pulsed laser over PEBA, or just laser only, did show a slightly deeper junction. This accounts for the improved V_{OC} achieved on the actual cells fabricated, which then leads to the conclusion that further work is still required to optimize pulse annealing for devices with a BSF.

The process verification phase was initiated for both small (2 x 2's) and large (3 in. dia.) cells, and will use those process steps and parameters still showing best promise.

Finally, during this period a high throughput laser system was conceptualized to accommodate three (3) inch diameter wafers at a rate of one per second.

SECTION 2

INTRODUCTION

This is the third quarterly report on a large spot, pulsed laser annealing contract for junction formation of phosphorus implanted, Czochralski grown, single crystal <100> silicon wafers. Work performed during the first two quarters included development of a 30mm diameter fused silica laser beam homogenizer with which good uniformity across an irradiated surface was achieved. Laser annealing parameters were developed with acceptability substantiated by Transmission Electron Microscopy, Secondary Ion Mass Spectrometry, and Rutherford Backscatter analysis. Small 2 x 2cm size cells were fabricated under various process conditions including: three different wafer surface conditions (chem-polished, flash etched, and texture etched); four laser energy densities; single and multiple pulse mode of operation; with and without BSF; 5 and 10 KeV front implant energy levels; Pulsed Electron Beam Anneal of $^{11}B/^{49}BF_2$ implants for BSF. Best results were achieved on a chem-polished substrate which had been ^{31}P implanted at 5 KeV, 2.5 x 10^{15} ions/cm^2 dosage, laser annealed at 1.5J/cm^2, with $^{49}BF_2$ back implants, PEBA, followed by laser pulsing over PEBA. The best of the limited quantities fabricated yielded a 14.7% AM 1 conversion efficiency.

During this reporting period, work centered around scaling up the sizes of cells laser annealed for evaluation from 2 x 2cm to 2 x 4cm. Also, the process verification phase of the contract was initiated. This phase makes use of only those candidate steps and parameters which still show promise in the fabrication of small cells, as well as the larger three (3) inch diameter size. Additionally, a high throughput pulsed laser system was conceptualized.

SECTION 3

TECHNICAL DISCUSSION

3.1 REFERENCE CELLS

A group of fifty (50) 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 1 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. The V_{OC} values for the cells without BSF are quite low, namely in the 440-460 mV range. Typically V_{OC} for these cells should be above 530 mV. The low V_{OC} output could have been caused by improper annealing with subsequent low activation of the implanted phosphorus ions. To verify the subpar output of these cells, another group of twenty-five (25) ion implanted cells were fabricated by furnace annealing under the same conditions as the previous group. These values, as shown in Table 2, are considered more representive.

3.2 LASER ANNEALING OF SCALED-UP SIZE CELLS

Fabrication of scaled-up cell sizes from 2 x 2cm to 2 x 4cm was completed this period. Two laser energy densities were used, 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, 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 3. Ranking the data by conversion efficiencies shows best results achieved on those cells with a screened-on and fired aluminum back surface

Table 1

ION IMPLANTED, FURNACE ANNEALED
THREE INCH DIAMETER REFERENCE CELLS

Cell No.	Description	V_{oc} (mV)	I_{sc} (A)	CFF (%)	η (%)	Comments
1	Polished, 5 KeV, No BSF	441	1.46	56.7	8.0	
2	" " "	454	1.50	60.6	9.0	
3	" " "	456	1.46	63.8	9.3	
4	" " "	—	—	—	—	Broke
5	" " "	452	1.52	66.3	10.0	
6	Polished, 5 KeV, BSF	—	—	—	—	Broke
7	" " "	568	1.53	72.5	13.8	
8	" " "	586	1.53	72.0	13.7	
9	" " "	—	—	—	—	Broke
10	" " "	568	1.53	72.0	13.7	
11	Polished, 10 KeV, No BSF	456	1.50	66.6	10.0	
12	" " "	—	—	—	—	Broke
13	" " "	456	1.52	66.0	10.0	
14	" " "	452	1.49	65.6	9.7	
15	" " "	452	1.49	65.6	9.7	
16	Polished 10 KeV, BSF	566	1.52	72.7	13.6	
17	" " "	569	1.54	72.9	14.0	
18	" " "	569	1.54	72.9	14.0	
19	" " "	578	1.50	73.7	14.0	
20	" " "	570	1.54	74.4	14.3	

Table 1 (Cont.)

Cell No.	Description	V_{oc} (mV)	I_{sc} (A)	CFF (%)	η (%)	Comments
21	Flash-Etched, 5 Kev, No BSF	465	1.50	66.7	10.4	
22	" " " "	465	1.48	64.7	9.8	
23	" " " "	—	—	—	—	Broke
24	" " " "	—	—	—	—	Broke
25	" " " "	—	—	—	—	Broke
26	Flash-Etched, 5 Kev, BSF	—	—	—	—	Broke
27	" " " "	576	1.55	72.1	14.1	
28	" " " "	576	1.55	72.1	14.1	
29	" " " "	576	1.55	72.1	14.1	
30	" " " "	—	—	—	—	Broke
31	Flash-Etched, 10 KeV, No BSF	453	1.49	65.9	9.5	
32	" " " "	453	1.49	66.5	9.8	
33	" " " "	453	1.47	67.4	9.8	
34	" " " "	455	1.49	65.5	9.8	
35	" " " "	450	1.49	66.4	9.8	
36	Flash-Etched, 10 KeV, BSF	—	—	—	—	Broke
37	" " " "	580	1.55	72.2	14.3	
38	" " " "	—	—	—	—	Broke
39	" " " "	—	—	—	—	Broke
40	" " " "	578	1.52	72.8	14.0	
41	Texture-Etched, 10 KeV, No BSF	476	1.44	68.9	10.4	
42	" " " "	445	1.49	67.6	9.8	
43	" " " "	440	1.49	68.0	9.8	

Table 1 (Cont.)

Cell No.	Description	V_{oc} (mV)	I_{sc} (A)	CFF (%)	η (%)	Comments
44	Texture-Etched, 10 KeV, No BSF	—	—	—	—	Broke
45	" " " "	440	1.49	69.0	10.0	

TABLE 2

ION IMPLANTED, FURNACE ANNEALED
THREE INCH DIAMETER REFERENCE CELLS, NO BSF

Cell No.	Description	V_{oc} (mV)	I_{sc} (A)	CFF (%)	(%)	Comments
P05 -1	Polished, 5 KeV	546	1.45	70.9	12.3	
-2		545	1.46	73.5	12.8	
-3		546	1.45	73.4	12.7	
-4		548	1.46	73.1	12.8	
-5		546	1.46	72.9	12.7	
P010-1	Polished, 10 KeV	555	1.44	74.3	13.0	
-2		551	1.44	73.8	12.8	
-3		548	1.44	74.2	12.8	
-4		553	1.46	73.0	12.9	
-5		551	1.44	74.3	12.9	
FE5 -1	Flash Etched, 5 KeV	540	1.43	73.5	12.4	
-2		540	1.45	73.6	12.6	
-3		--	--	--	--	Broke
-4		--	--	--	--	
-5		--	--	--	--	
FE10-1	Flash Etched, 10 KeV	547	1.45	73.2	12.7	
-2		546	1.47	72.9	12.8	
-3		548	1.44	73.6	12.7	
-4		549	1.46	73.0	12.8	
-5		549	1.46	73.0	12.8	
TE10-1	Texture Etched, 10 KeV	555	1.44	71.6	12.9	
-2		552	1.48	72.2	12.9	
-3		549	1.48	73.1	13.0	
-4		548	1.49	73.3	13.1	
-5		--	--	--	--	Broke

TABLE 3

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	70.2	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	68.5	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

field. Table 4 shows the results of the various process configurations, ranked by conversion efficiency groupings.

From the data shown in Table 4, the most promising processes at this juncture include:

1. Both chem-polished and flash-etched surface wafers.

2. Both 5 and 10 KeV ion implantation levels.

3. Laser anneal at $1.5J/cm^2$.

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 is 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 will thus be used for the balance of the cells requiring a BSF.

The ohmic contacting performed by ASEC originally called for vacuum deposited Ti-Pd-Ag with sintering at $600^{\circ}C$ for 10 minutes in an H_2 atmosphere. Even though the $600^{\circ}C$ should not introduce any dislocations or surface defects in the silicon substrate, it was determined that by first vacuum depositing aluminum for the P-contact followed by Ti-Pd-Ag, sintering at a lower temperature, $400^{\circ}C$ for 10 minutes in an N_2 atmosphere could be performed. Accordingly, all P-ohmic contacting was performed by ASEC in this manner.

3.3 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 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 lead to the brief work in this area.

Scanning Electron Microscope (SEM) photos, Figures 1 and 2, show representative texture etched surfaces before and after laser annealing. These photos are indeed

TABLE 4

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 4 (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

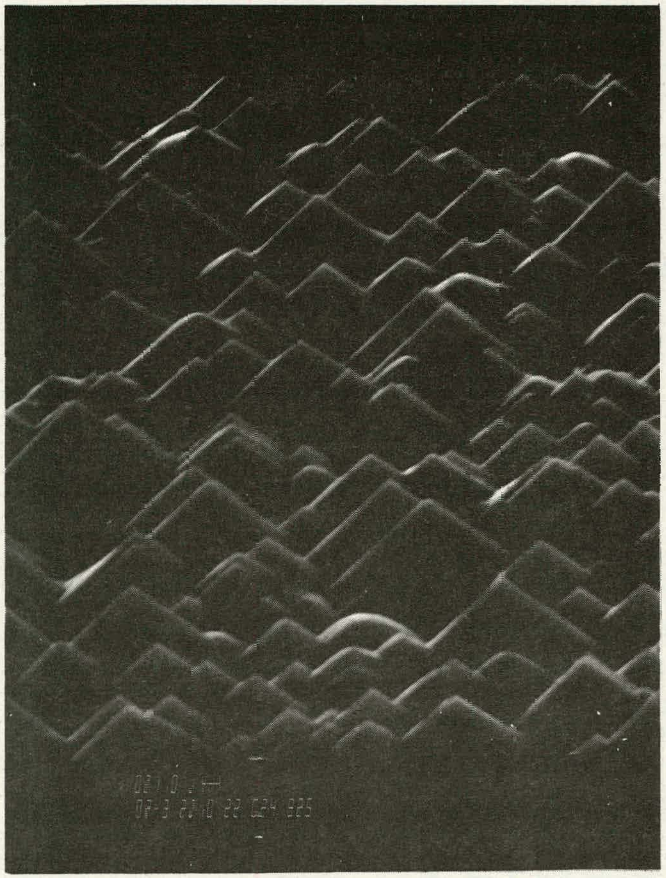


Figure 1

As Implanted, -2000X

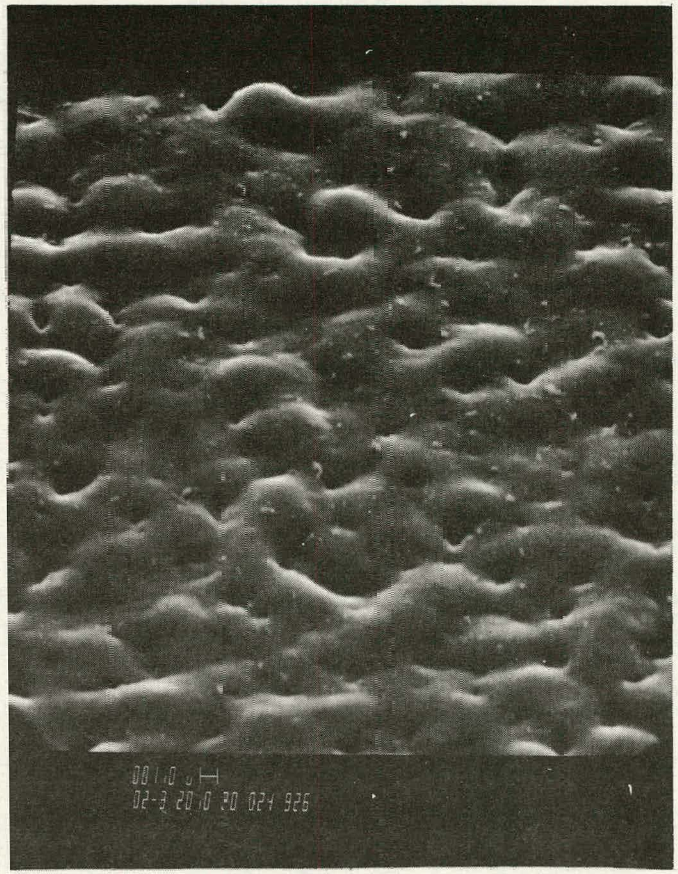


Figure 2

Pulsed Laser Annealed
1.2 J/cm^2 2000X

indicative of the extensive melt induced by laser irradiation on the textured surface.

Results on 2 x 2cm size textured cells are shown in Table 5.

TABLE 5

Electrical Output of Laser Annealed

2 x 2 cm Texture-Etched Cells

Cell No.	Description	V_{OC} (mV)	I_{SC} (mA)	CFF (%)	η
N1	10 KeV, 4×10^{15} Single Pulse, 1.2 J/cm^2	509	122	49.0	7.6
N2	" " "	520	127	65.4	10.8
N3	" " "	530	127	76.2	12.8
N4	10 KeV, 4×10^{15} Single Pulse, 1.5 J/cm^2	530	124	71.8	11.8
N5	" " "	546	127	70.7	12.3
N6	" " "	525	120	47.8	7.5

The above output conversion efficiencies coupled with those shown for 2 x 4's, Table 3, which ranged from 9 to 12.4%, reflect generally inferior output performances. A SIMS profile performed on the phosphorus doped front junction is shown in Figure 3. It appears from the figure that a very deep junction was formed, a condition not desirable for fabrication of high efficiency solar cells. It can be concluded, therefore, that pulsed laser processing is not compatible with texture-etched wafers. Accordingly, no further investigations will be performed with textured surface wafers.

3.4 JUNCTION DEPTH PROFILING

As reported in Quarterly Report No. 2, 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 1.5J/cm^2. SIMS analysis of sample wafers revealed

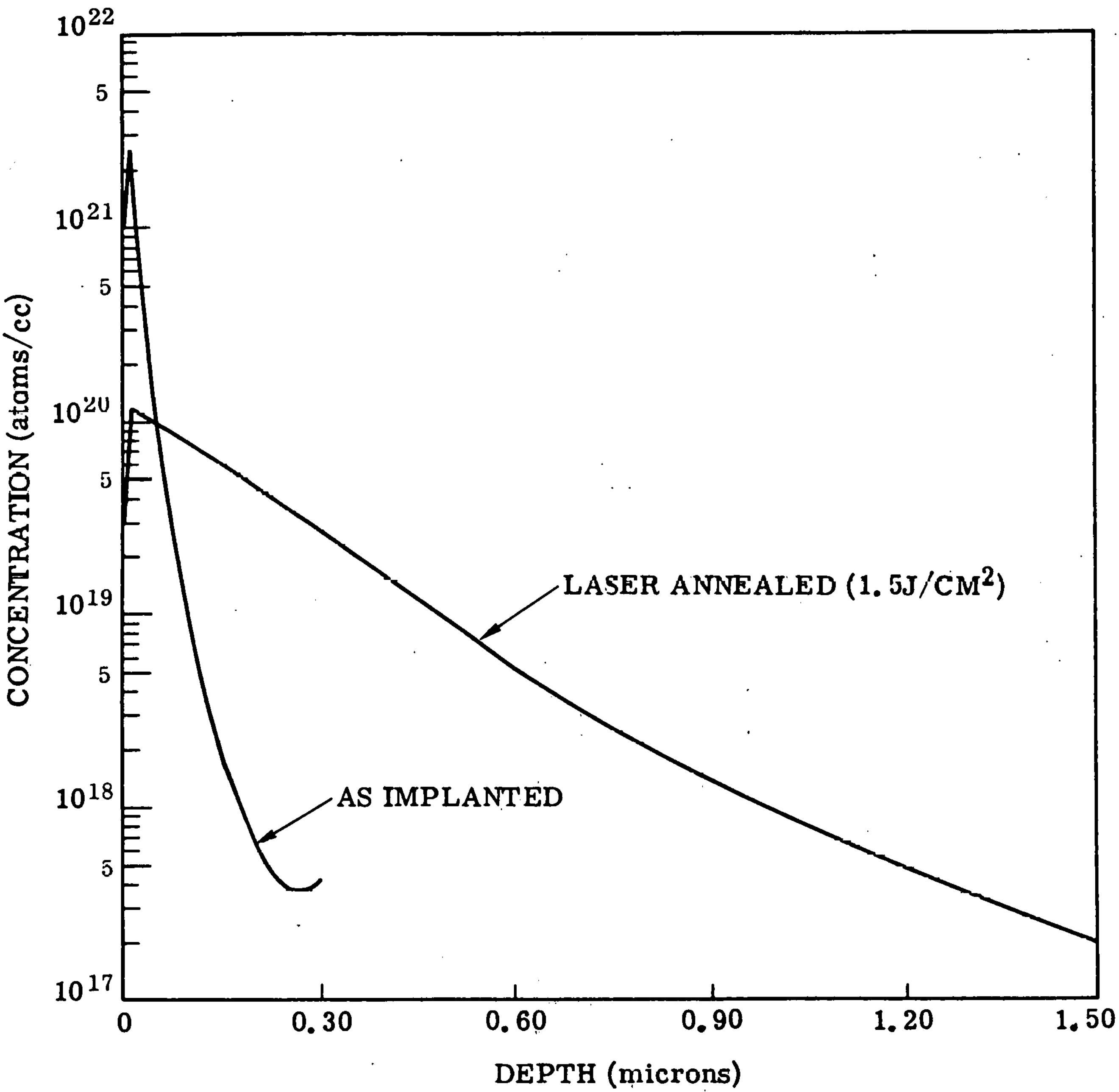


Figure 3. Depth profiles of phosphorus in texture etched silicon for as implanted and laser annealed specimens.

that the EB annealed profile differs very little from the implanted profile, Figures 4 and 5. Some dopant redistribution occurs, but the depth of the P^+ region remains essentially the same. From this it can be concluded that a 4000Å deep BSF on a 350μm thick wafer is not deep enough to cause the type of output improvements associated with a back surface field.

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

In Figures 4 and 5, 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 will 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 5, 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. Initially, the wafers were implanted with boron at 25 KeV, $5 \times 10^{15}/cm^2$. Evaluations following this implantation revealed that the boron implant does not anneal readily by electron beam processing. The implantation step was then repeated by SPIRE, but this time using BF_2 at 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.

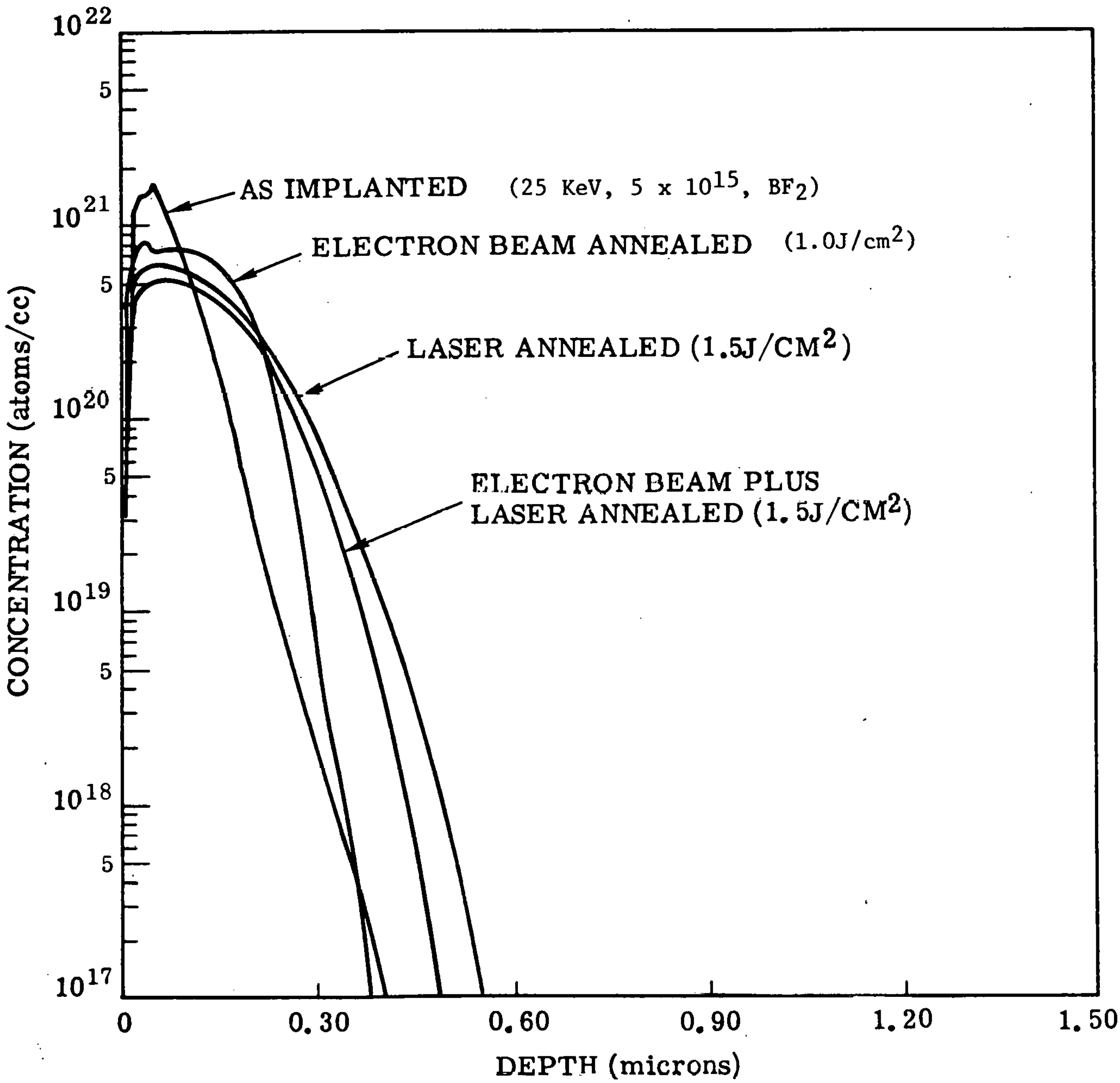


Figure 4 Depth profiles of boron in chem-polished silicon for as implanted, electron beam annealed, laser annealed, and electron beam plus laser annealed specimens.

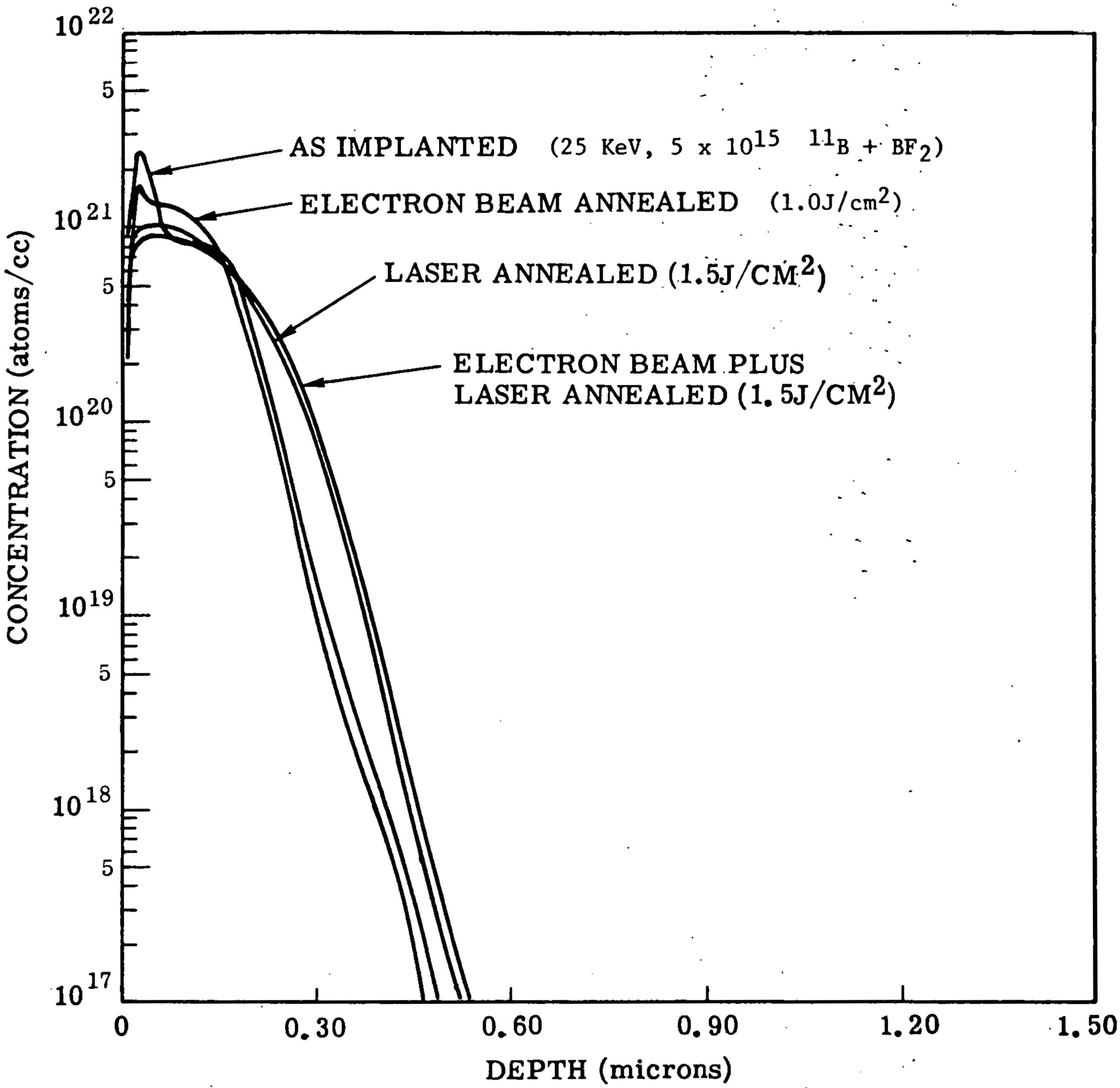


Figure 5. Depth profiles of boron in flash etched silicon for as implanted, electron beam annealed, laser annealed, and electron beam plus laser annealed specimens.

Because of the good results achieved with laser pulsing over the PEBA, some limited experimental work will be performed with ^{11}B implanted structures at 25, 50, and 150 KeV levels, followed by laser annealing only. This small effort will be accomplished in parallel with the on-going small cell process verification, currently in progress, and will be used for a preliminary view on the merits of laser annealing for back surface field formation. The depth of the boron diffusion at the 150 KeV energy level is projected to be, after annealing, approximately $.7\mu$, which on these 14 mil thick cells is not considered ideal. It obviously would be better on thinner (6-8 mil) wafers. The only available wafers at this time on which the work will be performed, however, are the 14 mil wafers purchased at the onset of this contractual work. The wafers had already been implanted in the front, and it was deemed that it would not be timely to purchase new wafers plus perform the required front implantation service.

3.5 IMPLANT DOSAGE ANALYSIS

As reported in Quarterly Report No. 2, SIMS analysis of 5 and 10 KeV $2.5 \times 10^{15}/cm^2$ implants revealed that the 10 KeV samples had a higher concentration of implanted species than their 5 KeV counterparts. This was puzzling since the exact reverse should have been observed. Analysis of the problem by SPIRE Corporation revealed that an apparent malfunction of the ion implanter led to a lower implant dose at 5 KeV from the required 2.5×10^{15}. To verify this occurrence, additional wafers were implanted at both energy levels, 5 KeV and 10 KeV, and will be subjected to SIMS analysis. Cells (2 x 2cm) will also be fabricated from these wafers and compared to original work.

3.6 PROCESS VERIFICATION

The process verification phase was started this period for both, small cells (greater than 200 in quantity) and large 3 inch diameter cells (48 in quantity). Process verification on small cells calls for both single pulse and multi-step overlap pulse annealing using those annealing parameters deemed best suited to date. The small cell work is being performed on 2 x 2cm size wafers which will accommodate both the single and multi-step overlap pulse annealing. The large three (3) inch diameters will be the first made using laser annealing under this contract. The still-candidate processing parameters consist of:

- Wafer Surface Condition: Chem-Polished and Flash Etched
- Cell Types: With and Without BSF
- Ion Implantation - Front Only: 5 and 10 KeV, 2.5×10^{15}, ^{31}P
- Laser Annealing Energy Density: $1.5 J/cm^2$
- BSF: Screened-on and Fired Aluminum Paste
- Ohmic Contacts: Vacuum Deposited Ti-Pd-Ag, 1 mil grid lines on front
  " " Al-Ti-Pd-Ag on back
- AR Coat: ASEC Multilayer AR Consisting of Al_2O_3 and TiO_2

For the large cells, 3 inches diameter, an automatic step and repeat controller was designed and implemented on the laser system. The controller provides the required commands to fire the laser and move the XY positioning table on which the wafer is located under the laser beam. The "programming" in the controller allows for complete wafer irradiation by virtue of 16 laser pulses in a span of 4 minutes.

3.7 HIGH THROUGHPUT LASER SYSTEM

One of the goals of this contract is to develop the criteria and concepts for a production type laser system capable of single pulse annealing of 7.62cm (3-inch) 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 is 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 by LMSC 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. This 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 76.2mm 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 decrease in system complexity, number of components (amplifiers), and cost of system operation.

SECTION 4

CONCLUSIONS

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

4.2 Implantation/pulse annealing parameters for a Back Surface Field formation require further development to optimize performance.

4.3 Screened and fired aluminum paste for a Back Surface Field formation yield acceptable performance in combination with front implant/laser annealed devices.

4.4 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 Conduct a greater in-depth evaluation for Back Surface Field formation by ion implantation/pulse annealing.

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

SECTION 6

NEW TECHNOLOGY

A concept for a high throughput pulsed laser system capable of a three (3) inch diameter spot size with a potential for annealing one (1) wafer per second has been established.

SCHEDULE PLAN

MODEL	PLAN	TITLE	PREPARED BY:	DATE
		LASER ANNEALING EVALUATION OF ION IMPLANTED SOLAR CELLS	M. Lopez	11-12-79
ISSUE NO.	REFERENCE		APPROVED BY:	DATE
	JPL 955696		Rev.	5-30-80 12-12-80

1.0 MTL PROCUREMENT & PROJ CONT.
 1.1 SUBMIT DEV. PLAN FOR JPL APPRO.
 1.2 PURCHASE WAFERS
 1.3 ION IMPLANT WAFERS. DELIVER UNANNEALED WAFERS TO JPL
 1.4 PROCESS CONTROL (REF) CELLS

2.0 HOMOGENIZE BEAM

3.0 DETERMINE SINGLE & MULTI-STEP LASER PARAMETERS AT 532, 1064 nm & COMB. ANALYZE

4.0 OPTIMIZE SINGLE PULSE ANNEAL & FABRICATE ~2 x 2 cm CELLS. ANALYZE & CORRELATE

5.0 OPTIMIZE MULTI-STEP ANNEAL & FABRICATE 2 x 4 cm CELLS ANALYZE & CORRELATE

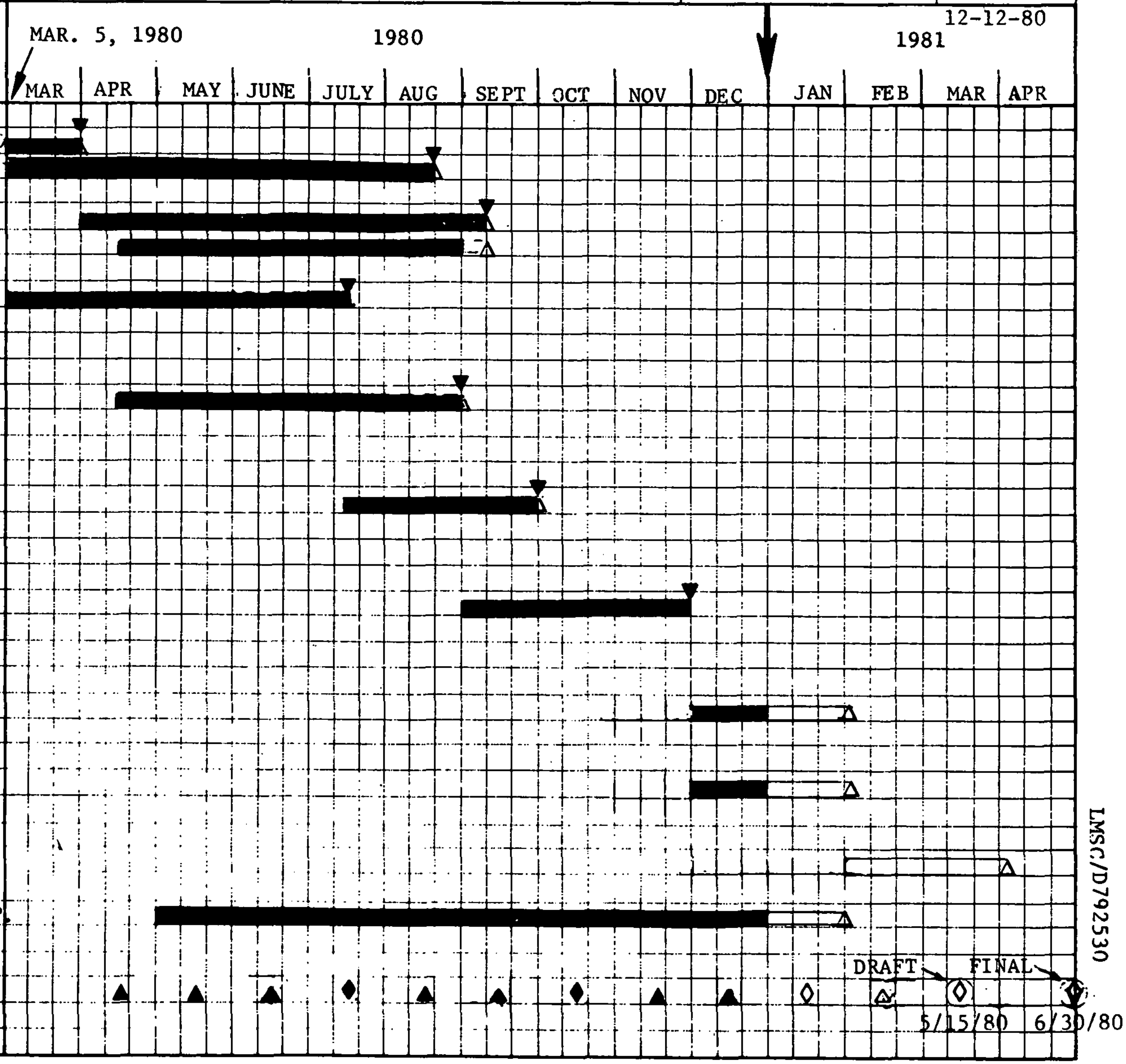
6.0 VERIFY PROCESS-SINGLE/MULTI PULSE BY FAB. SMALL (2x2 cm) CELLS & LARGER.

7.0 REPEAT PROCESS VERIFICATION USING 3.0 IN. DIA. WAFERS

8.0 FABRICATE 3.0 IN. DIA. CELLS & DELIVER TO JPL FOR EVAL.

9.0 DETERMINE LARGE DIA. PULSE EQUIP.

10.0 DOCUMENTATION (1) -SAMICS, TECH. PROGRESS & FINAL REPORTS.



FORM LMSC 481-3 Diezo Reproducible (1) △ = MONTHLY, ◇ = QTRLY ◎ = FINAL LOCKHEED MISSILES & SPACE COMPANY

LMSC/D792530