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EVALUATION OF THE ION IMPLANTATION PROCESS FOR
PRODUCTION OF SOLAR CELLS FROM SILICON
SHEET MATERIALS

Final Report for the Period December 15, 1982—December 1, 1983

By
M. B. Spitzer

December 1983

Work Performed Under Contract No. NAS-7-100-956381

Spire Corporation
Bedford, Massachusetts

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Contract No. 956381

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ABSTRACT

This report describes research on the evaluation of the ion implantation process for junction formation in present-day sheet materials, including Czochralski, edge-defined film-fed growth, heat exchanger method, SEMIX, SILSO and dendritic web. Both furnace annealing and low temperature pulsed electron beam annealing are examined and the presence of temperature effects is identified. It is shown that efficiency can be increased by optimization of the thermal processing. A comparison of ion implantation to alternative processes is made. The manner in which high efficiency may be achieved with each of these materials is discussed.

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A large number of individuals contributed to the work reported here. The program manager was Dr. R.G. Wolfson and the principal investigator was Dr. M.B. Spitzer. Mr. C.J. Keavney carried out process development studies and Mr. H.E. Drake supervised cell fabrication. Dr. D. Fitzgerald was the JPL technical manager for the program.

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SECTION 1

INTRODUCTION

The near-term commercialization of photovoltaic energy generation based on crystalline and polycrystalline silicon solar cell technology requires an increase in cell conversion efficiency and a decrease in solar cell cost. One approach to solar cell fabrication with the potential for such improvement is based on the use of ion implantation for junction formation.^(1,2) The ion implantation technique is characterized by high throughput, high process uniformity, and low process effluent.⁽²⁾ In addition, ion implantation has been shown to offer very high efficiency (18%, AM1) when combined with a high performance cell design.⁽³⁾ Thus, ion implantation may be the preferred junction formation technique for crystalline silicon solar cells.

The importance of process temperature to the performance of polycrystalline silicon solar cells has recently received attention from a number of investigators,⁽⁴⁻⁷⁾ and it has been suggested that reduction of process temperature may offer improvement in cell conversion efficiency. This advantage may arise from avoidance of high temperature activation of recombination centers at grain boundaries, diffusion and/or activation of impurities, as well as other reasons. Ion implantation, when properly combined with low temperature annealing,^(8,9) offers the possibility of low temperature junction formation and therefore may be the best technique for formation of junctions in polycrystalline silicon. Reduction of process temperature also simplifies the process and reduces its cost, owing to throughput advantages.

The primary obstacle to immediate and widespread acceptance of the ion implantation technique for solar cell production has been the high cost of ion implantation equipment. Recently, however, experiments have indicated that these costs can be reduced, if the ion implanter is dedicated to implantation of a single ion, by elimination of mass analysis.⁽¹⁰⁾ It was shown that cells of reasonably high efficiency can be obtained (about 15% AM1) without a strong dependence on process parameters.⁽⁹⁾ Indeed, low-cost production equipment should soon be available.⁽¹¹⁾ Owing to the potential of

the ion implantation process for achievement of high conversion efficiency,⁽³⁾ reduction of process temperature, and the anticipated cost reductions for implantation equipment, an investigation of the process applied to present-day silicon materials is of considerable interest, and is the subject of this investigation.

The objective of this program was therefore the evaluation of the capabilities of the ion implantation process for the production of photovoltaic cells from a variety of state-of-the-art, low-cost silicon sheet materials. Task 1 of the program involved application of ion implantation and furnace annealing to fabrication of cells made from dendritic web (WEB) silicon. Task 2 comprised the application of ion implantation and pulsed electron beam annealing (PEBA) to cells made from SEMIX, SILSO, Heat-exchanger method (HEM), edge-defined film-fed growth (EFG) and Czochralski (CZ) silicon.

An important aspect of this work was the investigation of the temperature sensitivity of the materials under study. Since junctions could be formed in the temperature range from room temperature to 950 C, we were able to examine the spectral response as a function of process temperature. Each of the materials displayed some temperature sensitivity, but the nature and extent of this sensitivity were found to vary for each material under study.

This report is divided into seven sections. In this section we have briefly summarized the object of the program and in Section 2 we summarize the cell fabrication processes used. Sections 3 and 4 report the data for Tasks 1 and 2, respectively, and Section 5 presents a discussion of the results and a non-exhaustive comparison to some of the data in the literature. Section 6 lists the conclusions and recommendations. Literature citations are listed in Section 7.

SECTION 2

DEVICE PROCESSING

In this section we review the device fabrication processes. It is important to note that the primary purpose of these studies was the investigation of the junction formation process; thus in most cases high efficiency features were intentionally omitted. Single crystal control solar cells were fabricated in all experiments and comparison of the cell data should be made to the controls whenever possible.

2.1 DENDRITIC WEB PROCESSING

All experiments with dendritic web processing were based on the n^+ -p- p^+ back surface field (BSF) solar cell structure. This design was chosen so that high efficiency features, such as oxide passivation and back surface reflectors, could be added sequentially after optimization of the n^+ and p^+ junctions. This structure had been previously shown to offer high performance with both dendritic web⁽¹²⁾ and Czochralski⁽²⁾ silicon.

Dendritic web strips are characterized by a thin web of material bordered on two sides by thicker edges (dendrites). The dendritic web strip is therefore not flat. Processing of such strips requires either accommodation or removal of the dendrites, which interfere with tooling designed for flat wafers. We elected to process web strips without dendrites so that we could use our standard laboratory tooling. It was therefore necessary to utilize extreme care in handling the web, since its resilience is lost when the dendrites are removed. Even with due care, significant process attrition was observed. In a production fabrication sequence that would utilize dedicated tooling, the dendrites could remain present throughout the process, thus obviating a yield problem. Our experience is not relevant to evaluation of process yield, since neither production tooling nor automation was employed.

The baseline cell fabrication sequence is replicated in Table 2-1. Junction formation consisted of boron implantation at 50 keV with a dose of 5×10^{15} ions/cm² to form the back p^+ layer, and phosphorus implantation at 10 keV with a dose of 2.5×10^{15} ions/cm² to form the front n^+ layer. Each implantation was followed by a

TABLE 2-1. BASELINE DENDRITIC WEB CELL FABRICATION SEQUENCE

-
1. CLEAN
 2. BACK IMPLANT

Ion Species	11B^+
Energy	50 keV
Dose	5×10^{15} ions/cm ²
 3. ANNEAL

550°C - 2 hours
950°C - 2 hours
 4. FRONT IMPLANT

Ion Species	31P^+
Energy	5 keV
Dose	2.5×10^{15} ions/cm ²
 5. ANNEAL

550°C - 2 hours
850°C - 15 minutes
550°C - 2 hours
 6. PHOTO PATTERN FRONT
 7. FRONT AND BACK CONTACT EVAPORATION

Ti-Pd-Ag

 8. METAL LIFTOFF
 9. SINTER
 10. PLATE FRONTS

10 μm of Ag

 11. SAW TO 2 cm x 2 cm
 12. TEST
-

specialized anneal design to produce a deep p^+ BSF and a shallow n^+ emitter. The BSF was formed first; a 950°C anneal was used to diffuse the back implant to a depth of approximately $1\ \mu\text{m}$. The front junction was formed after the BSF anneal to preclude diffusion of the phosphorus implantation during the 950°C anneal. This process had been previously shown to yield cells with high efficiency formed from 2 ohm-cm float zone silicon.⁽¹³⁾

The above implantation and anneal schedules resulted in front junctions with sheet resistance of 90 ohms-per-square and a depth of 0.4 micrometers. The resulting back p^+ implant had a doping concentration above $10^{19}\ \text{B}/\text{cm}^3$ to a depth of approximately 0.7 microns. Spreading resistance profiles for these implants are shown in Figures 2-1 and 2-2.

Metallization was formed by electron beam evaporation of Ti-Pd-Ag followed by sintering and electroplating. Front metallization was patterned by using the photolithographic lift-off process. In some cases a BSR (Section 3.4) was applied by evaporation of Al-Ti-Pd-Ag on the strip back, followed by a sinter at 400°C . The front contact was then applied after BSR formation.

Front metallization was plated to a line height of approximately $10\ \mu\text{m}$. The total shadow loss was limited to 3 to 4% in all cases. Cells were cut from the web strips using a diamond wheel dicing saw. The final cells were square; the area was $4\ \text{cm}^2$.

Antireflection (AR) coatings of Ta_2O_5 were applied by reactive electron beam evaporation. The coatings were found to increase the conversion efficiency of both web and float zone control cells by a factor of 1.41 (Section 3.4). The product of this measured factor and the efficiency measured on uncoated cells is a useful indicator of the conversion efficiency of AR-coated cells. In experiments in which AR-coatings have not been used this factor has been applied to project final cell efficiency.

FIGURE 2-1. SPREADING RESISTANCE ANALYSIS OF THE PHOSPHORUS FRONT JUNCTION IN DENDRITIC WEB SILICON.

FIGURE 2-2. SPREADING RESISTANCE ANALYSIS OF THE BORON BSF IN DENDRITIC WEB SILICON.

2.2 POLYCRYSTALLINE SHEET PROCESSING

The evaluation of junction formation processes for polycrystalline sheet materials comprised an investigation of novel emitter fabrication processes. An important aspect of this work was the investigation of the role of process temperature on base minority carrier lifetime, since temperature effects have been seen to be present in polycrystalline silicon.⁽⁴⁾ The optimization of BSF structures was not investigated.

The structure investigated was the n^+ -p solar cell structure without BSF. While a BSF may improve performance in some cases, the fabrication of a BSF would have interfered with the study of temperature effects, and would have introduced unnecessary complications in device fabrication. It should be noted that the n^+ -p devices fabricated in this study are not intended to be fully optimized. Rather, the purpose of this work was to evaluate the emitter fabrication process. Also, although the various sheet materials were largely co-processed, comparison of the cell performance for various materials was not our purpose nor would such a comparison be of utility, since no attempt was made to achieve the ultimate performance for each material.

The process sequence envisioned for the low-cost fabrication of cells from sheet materials involves ion implantation and rapid annealing (either brief thermal annealing or pulsed electron beam annealing). Table 2-2 illustrates the baseline cell fabrication process. Junctions are formed by ion implantation of phosphorus at 10 keV with a dose of 2.5×10^{15} ions/cm², followed by Spire's three-step thermal anneal. This anneal has proven to be effective for processing of Czochralski silicon⁽²⁾ and was used as a baseline anneal in this work. The resulting junction is essentially equivalent to the junction discussed in the previous section.

Back metallization consisted of full area electron beam evaporation of Al-Ti-Pd-Ag. Al was used to achieve good Ohmic contact to the unimplanted back surface. The sintering temperature was 400°C and therefore no BSF was formed. It is believed that there is negligible reflection at the Si-Al interface because the wafers were neither polished nor thin; the wafer thickness was approximately 380 μ m (15 mils) in most cases.

TABLE 2-2. BASELINE SHEET MATERIAL $n^+ - p$ PROCESS SEQUENCE

1. ACID ETCH
 2. IMPLANT FRONT

Ion Species	$31p^+$
Ion Energy	10 keV
Dose	2.5×10^{15} ions/cm ²
 3. ANNEAL

550°C - 2 hours
850°C - 15 minutes
550°C - 2 hours
 4. EVAPORATE BACK METALLIZATION

Al-Ti-Pd-Ag

 5. SINTER (400°C)
 6. PHOTOPATTERN FRONT
 7. EVAPORATE FRONT METALLIZATION

Ti-Pd-Ag

 8. METAL LIFTOFF
 9. SINTER (400°C)
 10. PLATE FRONTS

10 μ m of Ag

 11. SAW TO 2 cm x 2 cm
 12. TEST
-

Front contacts were applied by electron beam evaporation of Ti-Pd-Ag. The grid pattern was formed by the photolithographic lift-off process, and the grid was sintered and plated to a height of approximately 10 μm . The shadow loss was between 3 and 4% in all cases. The final cells were square; area was 4 cm^2 .

All pulsed electron beam annealing was performed with a SPI-PULSETM 7000, which annealed an area of about 80 cm^2 in a single pulse.⁽¹⁴⁾ The energy density was approximately 1 J/cm^2 . The pulse length was approximately 5×10^{-8} sec. These pulse parameters are believed to melt the surface which then regrows by liquid phase epitaxy.⁽¹⁵⁾

2.3 MEASUREMENTS

All cells were tested using simulated AM1 insolation, 100 mW/cm^2 . Cell temperature was maintained at 28°C by a water-cooled test block. Spectral response was determined with a filter wheel apparatus and a calibrated cell provided by NASA-LeRC. The diffusion lengths were determined from spectral response by the method of Stokes and Chu.⁽¹⁶⁾

SECTION 3

EXPERIMENTAL RESULTS--TASK 1

This section presents a full summary of the experiments performed with dendritic web in Task 1 and presents the data compiled. First, an analysis of the control wafers is presented. This is followed by a detailed description of each experiment. The experiments comprise an investigation of emitter formation, edge etching, surface passivation, and BSR fabrication.

3.1 FLOAT ZONE CONTROL WAFERS

Float zone wafers were used as controls for the web processing experiments. The material had resistivity of 1 ohm-cm, orientation of (111), a 2 inch diameter and was 450 μm (18 mils) in thickness, and was obtained from Wacker (WASO-S grade). Both front and back surfaces were polished. Polished surfaces and (111) orientation were utilized so as to be similar to the web surface, which is of (111) orientation. The web yields specular reflection, as grown, and is therefore similar to a polished wafer. The resistivity of the controls was at the low end of the resistivity range of the web strips studied (2-10 ohm-cm).

Table 3-1 lists the measured performance of control cells for each of the experiments. For the purposes of this comparison, subgroups have been combined. Note that in general, the cells are characterized by performance that is consistent with previous work at Spire.⁽²⁾ Each element in the table will be analyzed within the context of the experiments, but they are provided separately here to indicate that the cell processing was not characterized by large variations from the baseline process result, and that the processing was therefore well controlled.

The control material was evaluated after processing of baseline cells to determine the diffusion length, L_D . Figure 3-1 shows a calculation of open circuit voltage (V_{oc}) of the baseline cells as a function of L_D for two cases: back recombination velocity, s , equal to zero (perfect BSF) and s equal to infinity (Ohmic contact). Note that for diffusion length less than approximately 300 μm , the back surface field does not affect the V_{oc} . Measurement of the diffusion length indicates a value of at most, 250 μm . Thus, the controls cannot be used to determine the effectiveness of the BSF in the process experiments.

FIGURE 3-1. OPEN CIRCUIT VOLTAGE AS A FUNCTION OF BASE DIFFUSION LENGTH FOR FZ CONTROLS.

TABLE 3-1. PERFORMANCE OF FZ CONTROL SOLAR CELLS USED IN DENDRITIC WEB PROCESS EXPERIMENTS

Experiment (No. of cells)	V _{oc} (mV)	J _{sc} (mA/cm ²)	FF (%)	Eff (%)	Eff x 1.41 (%)
Baseline (10 cells)	584 (001)	23.2 (0.1)	78.6 (0.5)	10.6 (0.1)	14.9 (0.1)
5 keV Implant (7 cells)	588 (008)	21.7 (0.7)	73.7 (4.1)	9.41 (0.7)	13.3 (1.0)
10 keV Implant (10 cells)	602 (003)	22.4 (0.1)	76.3 (2.3)	10.3 (0.3)	14.5 (0.4)
BSR & Pass. (7 cells)	577 (011)	22.7 (0.8)	73.4 (3.8)	9.64 (0.7)	13.6 (1.0)

Notes: Insolation was AM1, 100 mW/cm², T = 28°C. Standard deviation shown in parenthesis.

3.2 BASELINE PROCESS

Using the sequence outlined in Section 2.1, dendritic web and FZ controls were co-processed to form n⁺-p-p⁺ solar cells. Performance data are replicated in Table 3-2.

The control cells were characterized by efficiency of approximately 15% which is typical of the performance usually attained with the baseline process.⁽²⁾ The FF of both the web and FZ indicates that the metallization process introduced only a small amount of parasitic resistance. Open circuit voltage, however, was much lower in the web cells, and in fact is lower than is typically obtained in web solar cells.⁽¹²⁾ The J_{sc} was also low. For comparison purposes, we replicate in Table 3-3 data obtained from the Westinghouse Electric Corporation. The performance achieved with the baseline process shown in Table 3-2 is characterized by V_{oc} and J_{sc} much less than both the Spire FZ control process data and the Westinghouse data.

TABLE 3-2. AVERAGE PERFORMANCE OF BASELINE DENDRITIC WEB BSF SOLAR CELLS

Group	V _{oc} (mV)	J _{sc} (mA/cm ²)	FF (%)	Eff (%)	Eff x 1.41 (%)
Dendritic Web (7 cells)	524 (008)	18.9 (0.7)	75.6 (1.0)	7.48 (0.40)	10.5 (0.6)
FZ Controls (10 cells)	584 (001)	23.2 (0.1)	78.6 (0.5)	10.6 (0.1)	14.9 (0.1)

Notes: Insolation was AM1, 100 mW/cm². T = 28°C. Cell area = 4 cm². The corrected efficiency is obtained by multiplying the efficiency obtained from a non-AR-coated cell by 1.41. This is the gain actually obtained with web and FZ (Table 3-11). Standard deviation shown in parenthesis.

TABLE 3-3. DENDRITIC WEB CELL PROCESSING RUNS

Run ID	Cell area (cm ²)	No. of cells in run	Average V _{oc} (V)	Average Eff. (%)
1118-1M	15.68	48	0.559	14.4
1127-1M	15.68	48	0.560	14.7
1209-49M	15.68	45	0.569	14.2
1126-25M	15.68	53	0.563	13.9
1201-25W	19.6	53	0.560	14.1
1201-1W	19.6	43	0.576	14.3
2234-49E	24.5	21	0.560	13.5

Notes: Courtesy of Westinghouse Electric Corporation. Used with permission.

The baseline web solar cells were theoretically modelled to determine the cause of the low V_{oc} . This modeling utilized measured values of cell thickness (T), resistivity (Ω), and short circuit current (J_{sc}) to determine theoretical values of diffusion length (L) and back surface recombination velocity (s) that could yield the observed performance. Table 3-4 lists the cell data used for the modeling and Table 3-5 lists parameters that were used to calculate V_{oc} .

Figure 3-2 indicates the results of the calculation for cell 521b. The dotted line in the figure indicates the experimental value of V_{oc} from Table 3-4. The calculation indicates that s is less than 2×10^3 cm/sec, and that L is at least $190 \mu\text{m}$. Figure 3-3, 3-4, and 3-5 illustrate the calculations for the other thicknesses and resistivities listed in Table 3-4. It can be seen that the experimental values of V_{oc} require low values of L. The results also indicate that s has only a small effect.

If we assume that the web is characterized by a diffusion length that is nearly equal in each strip, and that the ion-implanted BSF is characterized by a recombination velocity that is nearly equal at each p-p⁺ interface, then if we plot iso- V_{oc} lines as a function of L and s for the various cells (with various s and T), the lines should all cross at the actual values of L and s. Figure 3-6 illustrates the iso- V_{oc} plot. It can be seen that only two lines actually cross. The analysis therefore indicates variation in either L or s.

The control cells would not be sensitive to variations in s, as was shown in Section 3.1, thus they cannot be used to determine if the BSF is functional. However, spreading resistance analysis showed a good p-p⁺ junction (Figure 2-2). Furthermore, good Ohmic contact to the back was obtained in all cases, thus demonstrating the presence of a p⁺ region. It was therefore inferred that the cause of the poor performance was short diffusion length.

After consultations with the JPL and the Westinghouse Electric Corporation, it was determined that Spire's standard pre-process cleaning procedure and Westinghouse's standard procedure were different, and it was not clear whether the Spire process was adequate for use with dendritic web, although it is adequate for ordinary FZ slices. The short diffusion lengths were tentatively attributed to lack of the proper clean. The baseline experiment was considered complete and work in the task continued.

TABLE 3-4. BASELINE CELL THICKNESS AND RESISTIVITY DATA

Cell	Thick (μm)	RES (ohm-cm)	V_{oc} (mV)	J_{sc} (mA/cm ²)	FF (%)	Eff (%)
2a	250	11.2	521	18.91	74.2	7.31
2b	250	11.2	521	18.97	76.7	7.58
491a	170	7.3	518	18.22	74.5	7.03
491b	170	7.3	518	18.17	76.7	7.22
521b	175	12	521	18.35	75.6	7.22
562a	230	6	534	19.78	75.3	7.95
562b	230	6	536	19.68	76.4	8.06

TABLE 3-5. PARAMETERS USED IN CALCULATION OF BACK SURFACE RECOMBINATION SENSITIVITY

RES (ohm-cm)	N_A (cm ⁻³)	D (cm ² /sec)	J_{sc} (mA/cm ²)	n factor
11.2	1.20×10^{15}	32.6	18.94	1
7.3	1.84×10^{15}	31.7	18.20	1
12	1.12×10^{15}	32.7	18.35	1
6	2.22×10^{15}	31.3	19.73	1

FIGURE 3-2. CALCULATED OPEN CIRCUIT VOLTAGE AS A FUNCTION OF DIFFUSION LENGTH FOR 12 ohm-cm WEB CELLS.

FIGURE 3-3. CALCULATED OPEN CIRCUIT VOLTAGE AS A FUNCTION OF DIFFUSION LENGTH FOR 11.2 ohm-cm WEB CELLS.

FIGURE 3-4. CALCULATED OPEN CIRCUIT VOLTAGE AS A FUNCTION OF DIFFUSION LENGTH FOR 7 ohm-cm WEB CELLS.

FIGURE 3-5. CALCULATED OPEN CIRCUIT VOLTAGE AS A FUNCTION OF DIFFUSION LENGTH FOR 6 ohm-cm WEB CELLS.

FIGURE 3-6. ISO- V_{oc} PLOT FOR DIFFUSION LENGTH AND BACK SURFACE RECOMBINATION VELOCITY.

3.3 EMITTER MATRIX

A matrix was processed to optimize the emitter fabrication process. The cell fabrication shown in Figure 2-1 was used. Two implant energies were investigated: 5 keV and 10 keV, and two alternate three-step anneals were studied. The anneals consisted of 550°C-2 hrs. followed by 900°C or 950°C-15 min., followed by 550°C-2 hrs. Ramping was used between the steps to maintain minority carrier lifetime.

Table 3-6 lists the results of this experiment. The baseline process and the control cells have been included. The 10 keV control group was mixed owing to a process error, and it was not possible to separate the control cells annealed at 950°C from those annealed at 900°C. These are represented in the table combined as one group.

Consider first the control cells implanted at 5 keV. As the activation temperature is increased, the J_{sc} decreases. This is consistent with the diffusion of the junction, increase in junction depth, and consequent loss of blue response. The web, however, shows a larger variation in J_{sc} which probably masks the effect of the diffusion of the junction. Owing to this variation, there is no statistically significant difference between the various elements.

Implantation at 10 keV followed by activation annealing at 950°C was more promising and yielded the best results. It is interesting that the control cells had higher J_{sc} and V_{oc} than cells implanted at 5 keV. The explanation for this has not been determined.

It is evident from the emitter matrix experiment that the V_{oc} problems arising in the baseline cells persisted. To further study this, we examined the dark I-V (Figure 3-7) and spectral response (Figure 3-8) of representative cells. The dark I-V shows some parasitic series resistance. It can be seen that the diode quality is good and that the low V_{oc} is probably attributable to low diffusion length, as indicated by the spectral response.

In addition to the device measurements which indicated low diffusion length, we also investigated sources of edge leakage current. The edges of 12 web cells were etched in a 6-1-1 acid etch to remove edge damage that might have been introduced by the wafer dicing saw. The performance before and after etching is shown in Table 3-7.

TABLE 3-6. DENDRITIC WEB EMITTER MATRIX

31p+ implant energy	Three-step anneal temp (°C) (2 hrs, 15 min, 2 hrs)	Web				Float zone controls			
		V _{oc} (mV)	J _{sc} (mA/cm ²)	FF (%)	Eff (%)	V _{oc} (mV)	J _{sc} (mA/cm ²)	FF (%)	Eff (%)
5 keV	550/850/550°C (baseline)	524 (8)	18.9 (0.7)	75.6 (1.0)	7.48 (0.4)	584 (001)	23.2 (0.1)	78.6 (0.5)	10.6 (0.1)
5 keV	550/900/550°C	537 (29)	19.5 (1.7)	75.8 (0.7)	7.96 (1.05)	593 (2)	22.2 (0.2)	73.6 (4.8)	9.71 (0.6)
5 keV	550/950/550°C	515 (12)	17.4 (1.3)	75.5 (0.6)	6.77 (0.7)	582 (9)	21.0 (0.2)	73.8 (4.0)	9.0 (0.7)
10 keV	550/900/550°C	531 (15)	18.7 (1.0)	76.1 (1.5)	7.59 (0.62)	602 (003)	22.4 (0.1)	76.3 (2.3)	10.3 (0.3)
10 keV	550/950/550°C	554 (7)	19.9 (0.9)	73.9 (2.0)	8.28 (0.61)				

Notes: Insolation was AM1, 100 mW/cm². T = 28°C. Cell area = 4 cm². Standard deviation shown in parenthesis. Elements E and F in the control group were combined owing to a process error.

FIGURE 3-7. LOG (I)-V CHARACTERISTICS OF REPRESENTATIVE CELLS.

FIGURE 3-8. SPECTRAL RESPONSE OF REPRESENTATIVE CELLS. F12A IS A F2 CONTROL, W21A and W4A ARE WEB CELLS.

The V_{oc} and FF improved, but V_{oc} did not increase to acceptable levels. This result is consistent with measurements of dark I-V, which indicates that there is some leakage, but that V_{oc} appears to be controlled by low diffusion length. Note that the spectral response indicates a diffusion length that is far too short for any BSF action.

TABLE 3-7. AVERAGE PERFORMANCE OF 12 DENDRITIC WEB CELLS BEFORE AND AFTER EDGE ETCH

	V_{oc} (mV)	J_{sc} (mA/cm ²)	FF (%)	Eff (%)
Prior to etch	538 (16)	19.2 (1.1)	72.5 (9.5)	7.50 (1.22)
After etch	544 (18)	19.0 (1.0)	76.4 (1.1)	7.92 (0.63)

No AR coatings were used. J_{sc} not corrected for change in area.

3.4 BACK SURFACE REFLECTOR AND OXIDE PASSIVATION

Solar cells were fabricated from web that had both a BSR and front oxide passivation. The purpose of the BSR was to double the optical thickness of the cell and thereby increase J_{sc} . The oxide passivation has been shown to be effective in reducing the emitter saturation current.⁽³⁾ A fabrication process utilizing these elements was developed and is shown in Table 3-8.

The front implant was carried out at an energy of 5 keV and was annealed using 550°C-2 hrs, 850°C-15 min, 550°C-2 hrs, even though the emitter matrix experiment determined that a different set of parameters were ideal. The reason for use of the above process was that parallel work under a different contract⁽¹⁷⁾ indicated that the ideal parameters for use with oxide passivation could be substantially different than parameters for fabrication of optimal non-passivated emitters. Thus we chose to use the parameters which worked best with oxide passivation.

TABLE 3-8. BSR/OXIDE-PASSIVATION WEB CELL FABRICATION SEQUENCE

1. Clean
2. Back Implant

Ion species	11B+
Energy	50 keV
Dose	5×10^{15} ions/cm ²
3. Anneal

550°C--2 hrs.
950°C--2 hrs.
4. Front Implant

Ion species	31p+
Energy	5 keV
Dose	2.5×10^{15} ions/cm ²
5. Anneal/Oxidize

550°C--2 hrs.
850°C--15 min.
550°C--2 hrs.
6. Evaporate Back

Al-Ti-Pd-Ag

7. Sinter (400°C)
8. Photopattern Front
9. Evaporate Front

Ti-Pd-Ag

10. Metal Liftoff
11. Sinter
12. Plate Fronts

10 μ m of Ag

13. Saw to 2 cm x 2 cm
14. Test

The BSR was formed by evaporation of Al, followed by Ti-Pd-Ag. This approach was used in a recent NASA-funded program and yielded high reflectivity.⁽¹³⁾ The NASA process was used without modification in the present work.

Cell data is shown in Table 3-9. It can be seen that oxide passivation yields no statistically significant increase in V_{oc} , for either the controls or the web. J_{sc} is increased slightly, but whether this results from a slight reduction in front reflectivity or from a BSR effect is difficult to determine from this data. In Table 3-10, the individual selected cell data and diffusion length determined from the spectral response are shown. Spectral response for these cells is shown in Figure 3-9. Comparison of J_{sc} and L for cells with and without BSR is consistent with the possibility that BSR action is increasing J_{sc} , however, a definitive measurement of reflectivity has not been measured.

The cells were AR coated using evaporated Ta_2O_5 . Cell data before and after AR coating is shown in Table 3-11. A gain of 1.41 in efficiency was realized by this coating. Spectral response before and after AR coating is shown in Figures 3-10 and 3-11.

TABLE 3-9. RESULTS OF BSR AND OXIDE PASSIVATION
EXPERIMENT COMPARED TO BASELINE

Group	V _{oc} (mV)	J _{sc} (mA/cm ²)	FF (%)	Eff (%)
Web (11 cells)	535 (10)	20.8 (1.2)	76.6 (1.5)	8.54 (0.54)
Web Baseline (7 cells)	524 (8)	18.9 (0.7)	75.6 (1.0)	7.48 (0.40)
Controls (7 cells)	577 (11)	22.7 (0.8)	73.4 (3.8)	9.64 (0.70)
Control Baseline (10 cells)	584 (1)	23.2 (0.1)	78.6 (0.5)	10.6 (0.1)

Notes: Insolation was simulated AM1, 100 mW/cm². T = 28°C.
Standard deviation in parenthesis.

TABLE 3-10. PERFORMANCE AND DIFFUSION LENGTH DATA
FOR SELECTED CELLS

Cell ID	Mat. (FZ/Web)	BSR?	Passiv.?	L _D (μm)	V _{oc} (mV)	J _{sc} (mA/cm ²)	FF (%)	Eff (%)
2B	FZ	Yes	Yes	152	588	23.5	73.7	10.2
82D	Web	Yes	Yes	54	549	22.5	72.7	8.99
83D	Web	Yes	Yes	50	534	22.1	77.6	9.16
87D	Web	Yes	Yes	8	524	18.9	77.5	7.65
F12A	FZ	No	No	248	603	22.2	77.8	10.4
4A	Web	No	No	8	516	18.0	76.2	7.11
21A	Web	No	No	43	557	20.8	75.6	8.77

Notes: Insolation was simulated AM1, 100 mW/cm². T = 28°C. No AR
coating employed.

FIGURE 3-9. SPECTRAL RESPONSE FOR SELECTED BSR SOLAR CELLS. Cell 2B was fabricated from FZ. B2D, 83D and 87D were fabricated from web.

TABLE 3-11. CONVERSION EFFICIENCY BEFORE AND AFTER AR COATING

Group	V_{oc} (mV)	J_{sc} (mA/cm ²)	FF (%)	Eff (%)
<u>Before</u>				
Web (11 cells)	535 (10)	20.8 (1.2)	76.6 (1.5)	8.54 (0.54)
Controls (7 cells)	577 (11)	22.7 (0.8)	73.4 (3.8)	9.64 (0.70)
<u>After</u>				
Web (11 cells)	546 (13)	28.9 (1.7)	76.4 (1.3)	12.1 (0.9)
Controls (7 cells)	586 (9)	31.3 (1.0)	74.0 (3.5)	13.6 (0.9)

FIGURE 3-10. SPECTRAL RESPONSE OF AN FZ CONTROL CELL BEFORE AND AFTER AR COATING (cell 2B).

FIGURE 3-11. SPECTRAL RESPONSE OF A WEB CELL BEFORE AND AFTER AR COATING (cell 82D).

SECTION 4

EXPERIMENTAL RESULTS--TASK 2

In this section we present the results of emitter fabrication experiments on CZ, EFG, HEM, SEMIX and SILSO silicon sheet. The main objective of this work was the investigation of temperature effects resulting from the material processing. The analysis is based on a comparison of furnace annealing at various temperatures to room temperature pulse electron beam annealing (PEBA).

The baseline process described in Section 2 was applied to each of the materials under examination. The EFG, HEM and SEMIX were supplied by the JPL at the start of the program. The CZ and SILSO materials were obtained from Wacker. As will be explained in the relevant subsections, the outcome of the baseline experiments militated for replacement of the EFG, HEM and SEMIX with new materials. Subsequent experiments utilized new materials that were obtained directly from the manufacturers. A comparison of the data from the baseline process experiments to the data from the alternatives studied must be qualified by a statement that the materials may be quite different, owing to recent progress in sheet Si growth technologies.

The variations that were made to the baseline process comprised changes in implantation and anneal parameters. Implantation energies studied were 5, 10, and 15 keV. The dose was maintained at 2.5×10^{15} ions/cm² in all cases. Anneals with temperatures in the range of 550°C to 850°C were evaluated. Both 2 hr. single-step and 1.25 hr. two-step anneals were studied. The two-step anneals consisted of 15 min. at an experimental activation temperature followed by 1 hr. at 550°C. Pulsed electron beam annealing was also evaluated and compared to the thermal processes.

4.1 CZOCHRALSKI CONTROLS

Polycrystalline sheet materials were co-processed in all cases with 3 inch round Czochralski (CZ) control wafers obtained from Wacker. The material was of (100) orientation, polished on the front and etched on the back. The resistivity range was 7-15 ohm-cm and the wafer thickness was 380 μ m (15 mils).

4.1.1 Baseline CZ Data

Table 4-1 shows a summary of results obtained for baseline, one-step, and two-step furnace annealing, and pulsed electron beam annealing of CZ. The table shows the averages over all of the matrix elements in each experiment. These will be broken down later in this section. The average data in the table indicates that the baseline and two-step cell processing is typical of that obtained with furnace annealing. With a BSF, these cells would have V_{oc} of about 580 mV and efficiency of about 14%. It should be noted that the one-step furnace anneal and the pulsed electron beam annealed cells have, on the average, low fill factor. This must be considered when evaluating the results in the next sections. The low fill factor is attributable to faulty metallization for the one-step anneal cells. For PEBA cells, the low FF is believed to be the result of shunting which occurs in many, but not all, cells. For example, FF of up to 75.9% has been achieved for pulse annealed CZ cells (with efficiency of 9.48 without AR coating) in this work. Owing to the good results that have been obtained in some cases, it appears that the cause of the shunting is operator-dependent, but the source has not been identified in this work.

TABLE 4-1. PERFORMANCE OF CONTROL CELLS CO-PROCESSED WITH SHEET MATERIALS

Experiment (No. of cells)	V_{oc} (mV)	J_{sc} (mA/cm ²)	FF (%)	Eff (%)	Eff x 1.4 (%)
Baseline (10 cells)	533 (002)	22.3 (1.8)	73.5 (3.0)	9.07 (0.43)	12.8 (0.61)
One-Step thermal anneal (28 cells)	526 (2)	23.0 (1.4)	67.4 (9.8)	8.22 (1.46)	11.6 (2.1)
Two-step thermal anneal (20 cells)	533 (007)	24.1 (0.7)	73.8 (2.6)	9.48 (0.37)	13.4 (0.5)
PEBA (55)	516 (020)	23.2 (0.4)	67.9 (3.9)	8.32 (0.90)	11.7 (1.3)

Notes: Insolation was AM1, 100 mW/cm², T = 28°C. Standard deviation shown in parenthesis.

4.1.2 One-Step Annealing of CZ

Table 4-2 replicates data obtained on CZ control wafers in the one-step anneal experiments. It can be seen that a large variation in FF was observed, owing to back contact failure. Even after contact rework, the FF data were generally poor. Since the CZ control cells had failing metallization, the experimental data for the polycrystalline materials must be interpreted with some caution. Nevertheless, we believe the spectral response data to be presented to be largely unaffected by the low FF.

TABLE 4-2. ONE-STEP ANNEAL CZ CONTROL DATA

Temp (°C)	V _{oc} (mV)	J _{sc} (mA/cm ²)	FF (%)	Eff (%)	Eff x 1.41 (%)
550°C (10 cells)	521 (4)	23.8 (0.1)	68.5 (3.7)	8.50 (0.48)	12.0 (0.7)
650°C (5 cells)	522 (2)	23.8 (0.1)	65.9 (0.6)	8.18 (0.08)	11.5 (0.1)
750°C (4 cells)	524 (7)	20.3 (2.0)	48.1 (10.7)	5.19 (1.62)	7.32 (2.28)
850°C (9 cells)	535 (1)	22.9 (0.1)	75.6 (0.4)	9.28 (0.08)	13.1 (0.1)

Notes: Insolation was AM1, 100 mW/cm². T = 28°C. Standard deviation shown in parenthesis.

Spectral response data for the CZ cells processed with the one-step anneals are shown in Figure 4-1. Note that as the anneal temperature is increased, the blue response decreases, owing to the increased junction depth that results from diffusion of the implanted ions that occurs at higher temperatures. Also shown in the data is a severe decrease in the red response for the 750°C-2 hr. anneal. It should be noted that this cell had poor front layer metallization which could explain low J_{sc}, but it is not clear how low FF would decrease the red response to the extent shown. The data also suggests that the 850°C anneal offers higher diffusion length than the lower temperature anneals.

FIGURE 4-1. SPECTRAL RESPONSE FOR CZ CONTROLS PROCESSED WITH A SINGLE-STEP 2 HR. ANNEAL.

Figure 4-2 shows a comparison of this data to the spectral response obtained from a cell annealed using the pulsed electron beam. The data indicate that the 850°C anneal yields higher diffusion length than can be obtained from a non-heated wafer. However, the data are obtained on separate wafers; the variation seen here may be attributable to variations between wafers rather than in the process itself.

FIGURE 4-2. SPECTRAL RESPONSE OF 2 HR. SINGLE-STEP ANNEALS COMPARED TO PEBA.

4.1.3 PEBA Processing of CZ

Table 4-3 lists cell performance obtained using pulsed electron beam annealing. In this experiment, implantation energy was varied in order to determine the effect of implantation profile on annealing. It is found that the anneal is largely independent of implant energy. For PEBA processing, implantation energy of 10 or 15 keV appears preferable to 5 keV.

TABLE 4-3. AVERAGE AMI PERFORMANCE OF THE PEBA-PROCESSED CZ CONTROL GROUP

Implant energy	V_{oc} (mV)	J_{sc} (mA/cm ²)	FF (%)	Eff (%)	Eff x 1.41 (%)
5 keV (20 cells) 4436-1f	508 (25) 531	23.0 (0.3) 23.0	65.9 (2.5) 71.3	7.71 (0.67) 8.71	10.9 (0.9) 12.3
10 keV (15 cells) 4387-17f	521 (13) 534	23.3 (0.5) 23.4	68.9 (4.9) 75.9	8.39 (0.88) 9.48	11.8 (1.2) 13.4
15 keV (20 cells) 4335-2b	520 (18) 536	23.5 (0.2) 23.5	69.2 (3.8) 73.1	8.47 (0.77) 9.23	11.9 (1.1) 13.0

Notes: Insolation was AM1, 100 mW/cm². T = 28°C. Standard deviation shown in parenthesis. The best cell in each group is also indicated.

Note that the J_{sc} obtained with the PEBA process is comparable to the J_{sc} data shown in Table 4-2 for single-step thermal anneals. Thus, except for the 750°C anneal, the thermal processing seems to have a negligible effect on cell J_{sc} .

4.1.4 Two-Step Annealing of CZ

Two-step thermal anneal data are shown in Table 4-4. The implantation energy for this experiment was 5 keV with a dose of 2.5×10^{15} ions/cm². The cells are compared to the three-step baseline anneal, and it is evident that better results were obtained within the two-step anneal. This indicates that either the 5 keV ³¹P⁺ implant utilized in the present experiment is superior to the 10 keV ³¹P⁺ implant utilized in the baseline study, or that the diffusion length was degraded by the baseline process. The FF is also better than that which obtained in the baseline process, indicating that the cell improvement may be the result of improved processing techniques.

TABLE 4-4. AMI PERFORMANCE OF THE TWO-STEP FURNACE ANNEAL CZ CONTROL GROUP

Activation temperature	V _{oc} (mV)	J _{sc} (mA/cm ²)	FF (%)	Eff (%)	Eff x 1.41 (%)
550°C (5 cells)	526 (001)	24.3 (0.1)	71.1 (0.8)	9.09 (0.1)	13.2 (0.1)
650°C (5 cells)	529 (001)	24.3 (0.04)	71.9 (1.1)	9.24 (0.14)	13.4 (0.2)
750°C (5 cells)	533 (001)	23.9 (0.1)	75.2 (0.3)	9.60 (0.05)	13.9 (0.1)
850°C (5 cells)	543 (003)	23.9 (0.1)	77.1 (0.6)	10.0 (0.1)	14.5 (0.1)
3-Step (10 cells)	533 (002)	22.3 (1.8)	73.5 (3.0)	9.07 (0.43)	13.2 (0.6)

Notes: Insolation level is 100 mW/cm². T = 28°C. Area = 4 cm².
Standard deviation shown in parenthesis.

Examination of the data in Table 4-4 indicates that higher temperatures are preferred for processing of CZ using a two-step anneal. The higher temperatures yield better activation of the dopant thus reducing sheet resistance losses, as indicated by the dark I(V) curves shown in Figure 4-3. The sheet resistance of the emitter

FIGURE 4-3. DARK I-V CHARACTERISTICS OF THE CZ CONTROL CELLS.

annealed at 550°C was approximately 300 ohms-per-square whereas the sheet resistance after the 850°C anneal was approximately 80 ohms-per-square. In addition, the J_{sc} obtained was higher than that obtained with either the one-step or the PEBA process.

The external quantum efficiency of the control wafers processed with a two-step anneal has been measured and is shown in Figure 4-4. Increasing the activation temperature causes a decrease in the blue response. This is attributed to an increase in junction depth owing to diffusion during the anneal. The anomalous drop in red response for the two-step 750°C anneal was also observed in the one-step anneal experiments, as was the decrease in blue response with increasing anneal temperature. The PEBA data has been reproduced in Figure 4-4. It can be seen that the red response is somewhat higher for the thermally processed material.

4.1.5 Summary of CZ Diffusion Length Data

Diffusion length data were determined from the spectral response and are shown in Table 4-5. The highest diffusion length was obtained after annealing at 850°C; J_{sc} for this cell, however, was lower owing to the resultant increase in junction depth.

TABLE 4-5. CZ CELL PERFORMANCE AND DIFFUSION LENGTH DATA FOR DEVICES USED FOR SPECTRAL RESPONSE ANALYSIS

Cell	T (°C)	Time (min)	V_{oc} (mV)	J_{sc} (mA/cm ²)	FF (%)	Eff (%)	L_D (μm)
4387-17F	*** PEBA ***		534	23.4	75.9	9.48	129
4382-6D	550	15	526	24.3	71.3	9.11	122
4382-4B	650	15	531	24.2	71.5	9.20	127
4382-3F	750	15	533	23.9	75.5	9.61	93
4382-1E	850	15	541	24.0	77.4	10.07	128
4383-1E	550	120	521	23.9	73.5	9.16	91
4415-2A	650	120	524	23.8	66.6	8.29	115
4383-4D	750	120	529	22.2	59.4	6.98	18
4383-5B	850	120	534	22.9	75.3	9.23	144

Notes: Insolation was AM1, 100 mW/cm². T = 28°C. Diffusion length (L_D) was determined from spectral response. No AR coatings employed.

FIGURE 4-4. EXTERNAL QUANTUM EFFICIENCY OF CZ CONTROL CELLS ANNEALED WITH A TWO-STEP PROCESS.

The decrease in diffusion length after annealing at 750°C was observed in two separate experiments. Figure 4-5 illustrates the spectral response of cells processed with PEBA, 750°C-15 min., and 750°C-120 min. annealing. It can be conjectured that an oxygen effect is occurring here; such effects in CZ have been observed to occur at various temp.⁽¹⁸⁾ Osaka et al. have reported on the formation of oxide precipitates after annealing at 750°C⁽¹⁹⁾ and this effect may be occurring here. It would appear best to avoid processing CZ at 750°C.

FIGURE 4-5. COMPARISON OF SPECTRAL RESPONSE OF CELLS ANNEALED AT 750°C TO A PEBA-PROCESSED CELL.

4.2 EFG EXPERIMENTS

4.2.1 Baseline EFG Data

EFG ribbon, obtained from the JPL, was processed as described in Section 2. This material was observed to have SiC inclusions on both sides of the wafers. These inclusions can degrade FF if present on the front of the solar cell, and the baseline data in Table 4-6 suggest that this is occurring here. Also shown are the data for the co-processed CZ controls. Improved growth geometry now allows the growth of ribbon without SiC inclusions on the wafer front⁽¹⁹⁾ thus, the data in Table 4-6 is not representative of current performance that can be achieved with present-day EFG ribbon. We therefore chose to obtain new material for further studies.

TABLE 4-6. AVERAGE PERFORMANCE OF EFG BASELINE CELLS.

Group	V _{oc} (mV)	J _{sc} (mA/cm ²)	FF (%)	Eff (%)	Eff x 1.41 (%)
EFG (7 cells)	491 (021)	17.3 (0.7)	62.8 (9.6)	5.38 (1.12)	7.59 (1.57)
CZ-controls (10 cells)	533 (002)	22.3 (1.8)	73.5 (3.0)	9.07 (0.43)	12.8 (0.61)

Notes: Insolation was AM1, 100 mW/cm². T = 28°C. Standard deviation shown in parenthesis.

4.2.2 EFG Annealing Experiments

New EFG ribbon, obtained from the Mobil Solar Energy Corporation, was processed as described in the previous sections. Both single-step and two-step thermal anneals were studied and these were compared to PEBA processing.

Figure 4-6 indicates spectral response data for single step thermal annealing compared to a PEBA-processed cell, and Figure 4-7 shows the spectral response for two-step anneals. The performance data for the selected cells is shown in Table 4-7. These data indicate that high temperature processing of EFG is desirable, with very good results obtained with a two-step (850°C-15 min., 550°C-1 hr.) process. The high performance obtained with the 650°C-2 hr. anneal may be an anomolous result occurring in a particularly good starting wafer.

FIGURE 4-6. EXTERNAL QUANTUM EFFICIENCY OF EFG CELLS ANNEALED WITH A SINGLE-STEP PROCESS AND WITH PEBA.

FIGURE 4-7. EXTERNAL QUANTUM EFFICIENCY OF EFG CELLS ANNEALED WITH A TWO-STEP PROCESS AND WITH PEBA.

TABLE 4-7. EFG CELL PERFORMANCE AND DIFFUSION LENGTH DATA FOR DEVICES USED FOR SPECTRAL RESPONSE ANALYSIS

Cell	T (°C)	Time (min)	V _{oc} (mV)	J _{sc} (mA/cm ²)	FF (%)	Eff (%)	L _D (μm)
4435-9B	*** PEBA ***		418	19.5	61.7	5.04	37
4382-13D	550	15	508	21.1	73.9	7.91	45
4382-12C	650	15	513	21.1	69.8	7.56	38
4382-10A	750	15	521	21.6	71.5	8.06	42
4382-8D	850	15	516	22.3	72.9	8.38	59
4415-27C	550	120	495	20.8	55.6	5.74	44
4415-16B	650	120	498	22.6	58.9	6.64	53
4415-17B	750	120	508	21.4	69.8	7.58	60
4415-20D	850	120	531	21.5	69.1	7.90	48

Notes: Insolation was AM1, 100 mW/cm². T = 28°C. Diffusion length (L_D) was determined from spectral response. No AR coatings employed.

Average data for single step anneals of EFG are shown in Table 4-8. The FF is low for these cells owing to contact problems; however, it can be seen that the average J_{sc} increases with increasing temperature. The average data for the group processed at 650°C is not unusually high and therefore supports the conjecture that the spectral response shown in Figure 4-6 for 650°C is anomolous.

TABLE 4-8. AVERAGE CELL PERFORMANCE FOR EFG CELLS ANNEALED WITH SINGLE-STEP PROCESSES

Temp (°C)	V_{oc} (mV)	J_{sc} (mA/cm ²)	FF (%)	Eff (%)	Eff x 1.41 (%)
550°C (3 cells)	502 (10)	20.4 (0.9)	52.7 (2.5)	5.41 (0.40)	7.63 (0.56)
650°C (5 cells)	486 (7)	20.6 (1.3)	54.5 (11.4)	5.47 (1.23)	7.71 (1.73)
750°C (5 cells)	509 (2)	21.0 (0.5)	69.5 (1.8)	7.42 (0.24)	10.5 (0.3)
850°C (2 cells)	515 (23)	21.3 (0.3)	63.2 (8.3)	7.00 (1.34)	9.87 (1.89)

Notes: Insolation was AM1, 100 mW/cm². T = 28°C. Standard deviation shown in parenthesis.

Table 4-9 lists the average performance obtained for two-step anneals. High values of J_{sc} were achieved; however, the FF were low. The low FF are attributed to high sheet resistance probably resulting from an ion implantation dose error. Note that the J_{sc} increases with increasing current. This is an agreement with the single-step anneal results and is a strong indication that a high temperature anneal is beneficial to performance of EFG cells.

TABLE 4-9. AVERAGE AMI PERFORMANCE OF EFG CELLS PROCESSED WITH A TWO-STEP THERMAL ANNEAL

Activation temperature	V _{OC} (mV)	J _{SC} (mA/cm ²)	FF (%)	Eff (%)	Eff x 1.41 (%)
550°C (6 cells)	502 (005)	20.2 (0.5)	70.8 (2.5)	7.18 (0.43)	10.4 (0.6)
650°C (4 cells)	512 (002)	21.1 (0.3)	68.1 (1.5)	7.33 (0.16)	10.6 (0.2)
750°C (3 cells)	517 (006)	21.4 (0.2)	70.5 (3.3)	7.81 (0.46)	11.3 (0.7)
850°C (3 cells)	505 (009)	22.1 (0.3)	68.9 (3.6)	7.68 (0.62)	11.1 (0.9)

Notes: Insolation level is 100 mW/cm². T = 28°C. Area = 4 cm².
Standard deviation shown in parenthesis.

4.3 HEM EXPERIMENTS

The baseline HEM cells were fabricated from material that was well-characterized at JPL.⁽²⁰⁾ Since this material was of limited quantity, it was decided to use new HEM obtained from Crystal Systems for the remaining experiments. The well-characterized material would then be available for further studies, if warranted.

4.3.1 Baseline Cell Data

Table 4-10 shows the average performance of the baseline HEM cells. These cells compare well with the co-processed CZ control group. The higher V_{OC} can probably be attributed to the resistivity difference (HEM:6 ohm-cm, CZ:10 ohm-cm). The lower J_{SC} in the HEM cells is probably the result of shorter diffusion length in the polycrystalline HEM compared to that in CZ. It is interesting that the best cell is superior to the CZ controls. However, the performance of the CZ controls would be improved by addition of a BSF.

TABLE 4-10. AVERAGE PERFORMANCE OF HEM BASELINE CELLS

Group	V_{oc} (mV)	J_{sc} (mA/cm ²)	FF (%)	Eff (%)	Eff x 1.41 (%)
HEM (11 Cells)	553 (0.10)	20.3 (0.9)	74.0 (2.0)	8.33 (0.53)	11.7 (0.8)
CZ-control (10 Cells)	533 (0.02)	22.3 (1.8)	73.5 (3.0)	9.07 (0.43)	12.8 (0.6)
Best HEM Baseline Cell	567	21.9	74.6	9.25	13.0

Notes: Insolation was AM1, 100 mW/cm². T = 28°C. Standard deviation shown in parenthesis.

4.3.2 One-Step Anneal Data

Table 4-11 shows the average cell data obtained with one-step anneals. Recall that the control cells for the one-step anneals showed poor FF; this is also evident in the HEM data. Nevertheless, the data show increased V_{oc} and J_{sc} as a function of temperature, indicating improvement of diffusion length with higher processing temperatures.

TABLE 4-11. AVERAGE HEM CELL PERFORMANCE FOR ONE-STEP ANNEALS

Temp (°C)	V_{oc} (mV)	J_{sc} (mA/cm ²)	FF (%)	Eff (%)	Eff x 1.41 (%)
550°C (6 cells)	511 (2)	19.2 (2)	55.7 (0.1)	5.47 (0.36)	7.71 (0.51)
650°C (2 cells)	525 (1)	19.9 (0.5)	65.6 (1.4)	6.84 (0.05)	9.64 (0.07)
750°C (5 cells)	533 (1)	20.0 (0.4)	68.7 (0.6)	7.30 (0.19)	10.3 (0.3)
850°C (4 cells)	547 (4)	20.5 (0.4)	74.2 (0.3)	8.28 (0.22)	11.7 (0.3)

Notes: Insolation was AM1, 100 mW/cm². T = 28°C. Standard deviation shown in parenthesis.

Figure 4-8 shows the spectral response of cells selected from the groups listed in Table 4-11. Note that the lower process temperatures yield inferior performance, but that a PEBA-processed cell yields the best spectral response. It is also interesting that the 550°C anneal yielded the lowest blue response. This unusual result suggests the possibility of a process error, and so the results should be interpreted with some skepticism. Nonetheless, in all cases, the thermal processing would seem to be detrimental to the diffusion length, since the PEBA cell has the highest value.

FIGURE 4-8. SPECTRAL RESPONSE OF HEM SOLAR CELLS ANNEALED WITH A ONE-STEP PROCESS.

4.3.3 Two-Step Anneal Data

The average cell performance for the HEM cells is shown in Table 4-12. It is interesting that the performance improves with increasing temperature, as was the case for the one-step anneals. Figure 4-9 shows the spectral response of selected cells compared to a PEBA cell. The diffusion length appears to be degraded by the thermal processing; however, the least amount of degradation occurs for the processing at 850°C.

TABLE 4-12. AMI PERFORMANCE OF THE HEM GROUP ANNEALED WITH THE TWO-STEP PROCESS

Activation temperature	V _{oc} (mV)	J _{sc} (mA/cm ²)	FF (%)	Eff (%)	Eff x 1.41 (%)
550°C	529 (005)	20.5 (0.6)	74.3 (1.4)	8.07 (0.41)	11.4 (0.6)
650°C	520 (004)	18.9 (0.5)	73.9 (0.7)	7.25 (0.26)	10.2 (0.4)
750°C	526 (007)	19.2 (0.9)	73.5 (1.0)	7.42 (0.43)	10.5 (0.6)
850°C	549 (004)	21.2 (0.1)	76.2 (0.4)	8.86 (0.13)	12.5 (0.2)
3-Step	553 (010)	20.3 (0.9)	74.0 (2.0)	8.33 (0.53)	11.7 (0.7)

Notes: Insolation level is AM1, 100 mW/cm². T = 28°C. Standard deviation shown in parenthesis.

FIGURE 4-9. EXTERNAL QUANTUM EFFICIENCY OF HEM CELLS ANNEALED WITH THE TWO-STEP PROCESS.

4.3.4 PEBA Data

HEM cells were fabricated with various phosphorus ion implantation energies and annealed with a pulsed electron beam. Data for these cells is compiled in Table 4-13. Although some of the cells were found to be shunted, the efficiencies of the better cells were quite good and compare well with the furnace anneal process.

TABLE 4-13. AVERAGE AMI SOLAR CELL PERFORMANCE FOR THE HEM PEBA EXPERIMENTS

Implant energy	V _{oc} (mV)	J _{sc} (mA/cm ²)	FF (%)	Eff (%)	Eff x 1.41 (%)
5 keV (9 cells) 4436-20c	479 (16) 503	20.5 (0.3) 21.3	64.9 (5.1) 68.1	6.39 (0.68) 7.30	9.01 (0.96) 10.3
10 keV (15 cells) 4387-1c	517 (19) 542	21.1 (0.5) 21.5	68.8 (3.6) 73.3	7.50 (0.67) 8.53	10.6 (0.9) 12.0
15 keV (20 cells) 4435-20b	449 (17) 488	20.1 (0.8) 21.3	64.8 (3.3) 67.4	5.85 (0.5) 7.00	8.25 (0.71) 9.87

Notes: Insolation was AM1, 100 mW/cm². T = 28°C. Standard deviation shown in parenthesis.

4.3.5 Summary of HEM Diffusion Length Data

Table 4-14 indicates the solar cell performance for the cells selected for spectral response measurements. The spectral response measurements presented in Figures 4-8 and 4-9 indicated that the PEBA-processed cell (No. 4387-1c) had much better spectral response than the furnace annealed cells. It is possible that this cell was anomalous, however, several other cells in the group exhibited J_{sc} that was as good or better. In no case did the furnace annealed groups show such high values of J_{sc} . Thus, it would seem reasonable to conclude that the thermal processing does in some way degrade the cell performance; the degradation appears to be most severe at lower temperatures.

TABLE 4-14. HEM CELL PERFORMANCE AND DIFFUSION LENGTH DATA FOR DEVICES USED FOR SPECTRAL RESPONSE ANALYSIS

Cell	T (°C)	Time (min)	V _{oc} (mV)	J _{sc} (mA/cm ²)	FF (%)	Eff (%)	L _D (μm)
4387-1C	*** PEBA ***		542	21.5	73.3	8.53	64
4383-7A	550	120	508	19.3	58.6	5.76	10
4383-9D	650	120	531	19.5	72.2	7.47	23
4383-11A	750	120	534	20.3	69.2	7.52	22
4383-26A	850	120	552	20.9	74.3	8.56	25
4382-21D	550	15	533	21.2	75.6	8.56	30
4382-20D	650	15	521	18.9	74.7	7.34	9
4382-18D	750	15	531	19.9	72.6	7.65	11
4382-16D	850	15	551	21.2	76.5	8.96	19

Notes: Insolation was AM1, 100 mW/cm². T = 28°C. Diffusion length (L_D) was determined from spectral response. No AR coatings employed.

4.4 SEMIX EXPERIMENTS

SEMIX experiments began with material supplied by the JPL. This material was etched to approximately 150 microns and owing to the thickness, the yield for the baseline experiment was zero. New material, obtained from SEMIX Corporation, was used for the one-step anneal, two-step anneal and PEBA experiments.

4.4.1 One-Step Anneals

Table 4-15 indicates the results achieved by one-step annealing of SEMIX. Although the FF of these cells is low, the average J_{sc} and V_{oc} increase with temperature. The scatter in this data is large, however, so it is not possible to draw a reliable conclusion about the effects of thermal processing from this data.

TABLE 4-15. AVERAGE SEMIX PERFORMANCE FOR ONE-STEP ANNEALS

Temp (°C)	V _{oc} (mV)	J _{sc} (mA/cm ²)	FF (%)	Eff (%)	Eff x 1.41 (%)
550°C (5 cells)	518 (6)	21.0 (1.2)	43.2 (4.3)	4.71 (0.65)	6.64 (0.92)
650°C (7 cells)	528 (10)	21.4 (1.1)	66.7 (2.5)	7.53 (0.53)	10.6 (0.7)
750°C (8 cells)	537 (11)	21.6 (1.0)	60.3 (7.7)	7.03 (1.0)	9.91 (1.41)
850°C (2 cells)	534 (11)	21.6 (1.5)	68.8 (2.6)	7.95 (0.45)	11.2 (0.6)

Notes: Insolation was AM1, 100 mW/cm². T = 28°C. Standard deviation shown in parenthesis.

Figure 4-10 illustrates the spectral response of selected cells compared to a cell processed with PEBA. In general, the thermally-annealed cells have superior blue response and equivalent red response. The exception is the cell annealed at 850°C, which shows a lower diffusion length than was obtained with PEBA. A second cell annealed at 850°C (not shown) had much higher V_{oc} and J_{sc}. Thus, it is possible that the result shown in Figure 4-10 for annealing at 850°C is attributable to an anomalous process error or to the starting material itself.

4.4.2 Two-Step Anneals

Two-step anneals of SEMIX were carried out, but unfortunately severe metallization problems reduced the FF to very low levels. Still, J_{sc} data was obtained for two-step anneals at three temperatures; this data is shown in Table 4-16. It can be seen that the J_{sc} is somewhat independent of the processing temperature.

FIGURE 4-10. SPECTRAL RESPONSE OF SEMIX CELLS PROCESSED WITH A ONE-STEP ANNEAL.

TABLE 4-16. AVERAGE J_{SC} FOR SEMIX CELLS PROCESSED WITH A TWO-STEP ANNEAL

Wafer No.	Temp (°C)	Number of cells	J_{SC} (mA/cm ²)	Stand. Dev. (mA/cm ²)
19	750	3	20.7	0.4
20	750	3	22.3	0.2
21	650	3	20.9	1.1
25	550	3	21.3	1.2

Notes: Insolation was AM1, 100 mW/cm². T = 28°C.

4.4.3 PEBA Processing

Table 4-17 indicates the data obtained for samples annealed with a pulsed electron beam. Note that the J_{SC} of the best cells was inferior to cells formed by thermal annealing owing to the lower blue response (see Figure 4-10). The average J_{SC} , FF and V_{OC} were also low compared to the thermal anneals.

TABLE 4-17. AVERAGE AMI SOLAR CELL PERFORMANCE FOR THE SEMIX PEBA EXPERIMENTS

Implant energy	V_{OC} (mV)	J_{SC} (mA/cm ²)	FF (%)	Eff (%)	Eff x 1.41 (%)
5 keV (8 cells) 4436-15c	467 (33) 516	19.6 (2.1) 21.7	66.7 (2.0) 69.2	6.10 (1.15) 7.73	8.60 (1.62) 10.9
15 keV (7 cells) 4435-16d	457 (44) 500	20.8 (1.6) 21.5	66.1 (2.1) 69.3	6.34 (1.10) 7.47	8.94 (1.55) 10.5

Notes: Insolation was AM1, 100 mW/cm². T = 28°C. Standard deviation shown in parenthesis.

4.4.4 Summary of Diffusion Length Data

Table 4-18 lists the diffusion length data for the cells used in the spectral response measurements. Note the exceptionally high values of L_D . We infer from this data that thermal processing has little effect on the diffusion length measured in SEMIX silicon.

TABLE 4-18. SEMIX CELL PERFORMANCE AND DIFFUSION LENGTH DATA FOR DEVICES USED FOR SPECTRAL RESPONSE ANALYSIS

Cell	T (°C)	Time (min)	V _{oc} (mV)	J _{sc} (mA/cm ²)	FF (%)	Eff (%)	L _D (μm)
4435-16D	*** PEBA ***		500	21.5	69.3	7.47	86
4415-21C	550	120	524	22.0	47.9	5.52	67
4415-23B	650	120	539	22.6	68.5	8.34	84
4415-25D	750	120	544	22.7	66.9	8.27	84
4415-26C	850	120	526	20.5	70.6	7.63	43

Notes: Insolation was AM1, 100 mW/cm². T = 28°C. Diffusion length (L_D) was determined from spectral response. No AR coatings employed.

4.5 SILSO EXPERIMENTS

Starting material for SILSO experiments consisted of 10 cm x 10 cm wafers. Squares were cut from the center of the wafers (5 cm x 5 cm) so that each wafer would have approximately the same grain size. Baseline, one-step, two-step and PEBA experiments were all conducted from material from the same starting lot.

4.5.1 Baseline SILSO Experiments

Table 4-19 shows a comparison of the baseline SILSO cell data to the CZ controls. Fairly good performance was achieved on all of the cells.

TABLE 4-19. AVERAGE PERFORMANCE OF SILSO BASELINE CELLS

Group	V_{oc} (mV)	J_{sc} (mA/cm ²)	FF (%)	Eff (%)	Eff x 1.41 (%)
SILSO (15 cells)	523 (005)	20.8 (0.3)	75.0 (1.8)	8.15 (0.25)	11.5 (0.4)
CZ-controls (10 cells)	533 (002)	22.3 (1.8)	73.5 (3.0)	9.07 (0.43)	12.8 (0.6)

Notes: Insolation was AM1, 100 mW/cm². T = 28°C. Standard deviation shown in parenthesis.

4.5.2 One-Step Anneal Experiments

Table 4-20 presents the data for the one-step thermal anneals of SILSO. The best J_{sc} was obtained at temperatures of 650°C and 750°C. The spectral response shown in Figure 4-11 indicates that L_D appears to be degraded most by processing at 550°C or 850°C. It is interesting to note that the PEBA cell to which comparison is made has good blue response. The reason for this is not clear.

4.5.3 Two-Step Annealing Experiments

Cells were fabricated from SILSO using two-step furnace annealing and cell performance data are shown in Table 4-21. Best results were obtained with an activation temperature of 850°C. The results, however, show a curious decrease in efficiency in the temperature range of 650°C to 750°C. Examination of the quantum efficiency (Figure 4-12) shown a decrease in blue response owing to in-diffusion of the junction, and a decreased red response for the 650°C and 750°C matrix elements. This data would seem to contradict the data from the one-step anneals.

FIGURE 4-11. SPECTRAL RESPONSE OF SILSO CELLS PROCESSED WITH ONE-STEP ANNEALING.

TABLE 4-20. AVERAGE SILSO PERFORMANCE FOR ONE-STEP ANNEALS

Temp (°C)	V _{oc} (mV)	J _{sc} (mA/cm ²)	FF (%)	Eff (%)	Eff x 1.41 (%)
550°C (6 cells)	518 (2)	21.3 (0.2)	68.6 (4.6)	7.55 (0.44)	10.6 (0.6)
650°C (6 cells)	517 (1)	21.2 (0.2)	61.2 (2.0)	6.69 (0.23)	9.43 (0.32)
750°C (3 cells)	525 (1)	21.0 (0.1)	68.1 (0.8)	7.51 (0.09)	10.6 (0.1)
850°C (3 cells)	527 (2)	20.5 (0.01)	72.5 (3.5)	7.86 (0.39)	11.1 (0.5)

Notes: Insolation was AM1, 100 mW/cm². T = 28°C. Standard deviation shown in parenthesis.

TABLE 4-21. AVERAGE SILSO AMI PERFORMANCE FOR THE TWO-STEP ANNEALS

Activation temperature	V _{oc} (mV)	J _{sc} (mA/cm ²)	FF (%)	Eff (%)	Eff x 1.41 (%)
550°C	519 (0.01)	21.5 (0.3)	73.6 (0.2)	8.20 (0.12)	11.9 (0.2)
650°C	514 (0.05)	21.0 (0.6)	73.3 (0.5)	7.91 (0.29)	11.5 (0.4)
750°C	519 (0.03)	21.1 (0.2)	73.8 (0.4)	8.07 (0.12)	11.7 (0.2)
850°C	528 (0.06)	21.4 (0.4)	75.8 (0.5)	8.56 (0.24)	12.4 (0.3)

Notes: Insolation level is 100 mW/cm². T = 28°C. Area = 4 cm². Standard deviation shown in parenthesis.

FIGURE 4-12. SPECTRAL RESPONSE OF SILSO CELLS PROCESSED WITH A TWO-STEP THERMAL ANNEAL.

4.5.4 PEBA Experiments

Table 4-22 indicates the data obtained from cells formed by pulsed electron beam annealing. Best results were obtained with an implant energy of 10 keV, and very high values of J_{sc} were obtained compared to thermal processing. This data would indicate that the SILSO is sensitive to thermal processing.

TABLE 4-22. AVERAGE AMI SOLAR CELL PERFORMANCE FOR THE SILSO PEBA EXPERIMENTS

Implant energy	V_{oc} (mV)	J_{sc} (mA/cm ²)	FF (%)	Eff (%)	Eff x 1.41 (%)
5 keV (12 cells) 4436-13a	445 (30) 516	21.0 (1.0) 23.1	65.4 (0.8) 66.2	6.13 (0.74) 7.89	8.64 (1.04) 11.1
10 keV (15 cells) 4387-14c	525 (5) 531	22.3 (0.5) 22.8	70.9 (1.9) 73.1	8.29 (0.34) 8.85	11.7 (0.48) 12.5
15 keV (14 cells) 4435-10c	472 (22) 490	21.9 (0.4) 21.7	64.4 (2.2) 68.0	6.65 (0.44) 7.23	9.38 (0.62) 10.2

Notes: Insolation was AM1, 100 mW/cm². T = 28°C. Standard deviation shown in parenthesis.

4.5.5 Summary of Diffusion Length Data

Table 4-23 lists the summary of the data for SILSO cells used for spectral response analysis. Note that the PEBA cell has L_D of about twice as much as the thermally-processed material. J_{sc} and V_{oc} are also somewhat higher, which supports the conjecture that thermal processing is important in SILSO material.

TABLE 4-23. SILSO CELL PERFORMANCE AND DIFFUSION LENGTH DATA
FOR DEVICES USED FOR SPECTRAL RESPONSE ANALYSIS

Cell	T (°C)	Time (min)	V _{oc} (mV)	J _{sc} (mA/cm ²)	FF (%)	Eff (%)	L _D (μm)
4387-14C	*** PEBA ***		531	22.8	73.1	8.87	87
4383-14D	550	120	518	21.3	71.5	7.88	47
4383-15D	650	120	516	21.3	64.3	7.07	65
4383-18D	750	120	526	21.0	69.0	7.62	58
4383-28B	850	120	526	20.6	75.1	8.13	46
4382-30C	550	15	521	21.8	73.6	8.34	49
4382-28C	650	15	510	20.6	73.4	7.74	40
4382-25D	750	15	521	21.1	73.7	8.10	46
4382-24D	850	15	531	21.7	76.3	8.80	56

Notes: Insolation was AM1, 100 mW/cm². T = 28°C. Diffusion length (L_D) was determined from spectral response. No AR coatings employed.

SECTION 5

DISCUSSION

It is evident from the data presented in the previous sections that careful thermal processing is important to solar cell fabrication from Si sheet materials. In this section we compare the results obtained in the present work with data from the literature. In this way we can form an evaluation of the ion implantation process and draw comparisons to alternate technology.

5.1 DENDRITIC WEB

Experiments on dendritic web illustrate the importance of careful thermal processing. In all web cells that had a BSF formed by annealing for 2 hrs. at 950°C, the V_{oc} and J_{sc} were degraded. In prior work on the ion implantation process applied to dendritic web,⁽²⁰⁾ in which a long high temperature BSF anneal was not used, better results were obtained. In fact, a comparison between ion implanted cells and cells formed by gaseous diffusion was made on cells formed from the same web crystal. The data from this experiment are replicated in Table 5-1. This experiment showed that both higher efficiency and a more narrow process distribution were obtained from the ion implantation process.

TABLE 5-1. AM1 PERFORMANCE COMPARISON OF ION IMPLANTED CELLS TO DIFFUSED CELLS FROM THE SAME WEB CRYSTAL

Group	V_{oc} (mV)	I_{sc} (A)	FF (%)	Eff. (%)
Ion Implanted (12 cells)	561 (9)	0.486 (0.025)	0.738 (0.021)	13.1 (0.8)
Diffused (12 cells)	538 (11)	0.422 (0.051)	0.786 (0.034)	12.2 (0.9)

Cell area is 15.04 cm². All measurements were conducted at Westinghouse.

5.2 EFG RIBBON

Our results demonstrate the value of a high temperature process step to performance of cells made from EFG ribbon. The spectral response was shown to increase after high temperature annealing, and higher J_{sc} was obtained by thermal annealing than was obtained with PEBA. This work indicates that ion implantation with thermal annealing may be a very promising junction formation process for EFG. Since the annealing can be carried out over a wide range of temperature and time, it can be tuned to yield the maximum increase in bulk diffusion length.

These results are in agreement with prior experimental work on this subject.⁽²¹⁾ In the earlier work, it was shown that treatments at 800°C in PH_3 could lead to enhanced cell performance, but that treatments in N_2 did not. It was suggested that the mechanism was gettering by the PH_3 diffusion occurring at the surface. In the present work, in which $^{31}P^+$ implantation is used, gettering may also be present. Based on the present work, a two-step anneal (850°C-550°C) appears best, but whether the 550°C is actually necessary has not been determined.

The conversion efficiencies obtained here also compare well with prior work,⁽²²⁾ in which average efficiencies of 10 to 11% were obtained. We AR-coated two cells and achieved efficiencies of 10.2% and 10.7%. In both cases, a gain in efficiency of 34% was obtained. With an optimized thermal process, high quality AR coating and high efficiency device processing (oxide passivation, optimized metallization), efficiency of over 12% should be attainable.

5.3 HEM

The results of experiments on HEM silicon indicate the presence of important temperature effects that occur during junction processing. PEBA results were found to offer superior spectral response, yet nearly equal J_{sc} . For example, consider Table 4-14. PEBA cell 4387-1C was found to have a diffusion length of 64 μm whereas thermally-annealed cell 4382-16D had a diffusion length of 19 μm , yet the J_{sc} 's were nearly equal (21.5 mA/cm² and 21.2 mA/cm²). This indicates to us the possibility of light-enhanced diffusion length. It would seem that after high temperature processing, the "dark" diffusion length is degraded, yet at AM1 high J_{sc} is obtained. In the one-step

anneals, this degradation was most severe for cells processed at 550°C. The two-step anneals showed degradation at 650°C and 750°C, but these steps were followed by an anneal by 550°C for 1 hr. The only obvious conclusion to be drawn is that temperature effects are active here and warrant further study. It is not clear whether efficiency increases with increasing process temperature, or whether there exists a minimum in efficiency in the range of 700°C.

The temperature sensitivity of HEM indicates the importance of careful high temperature processing and the possible desirability of PEBA processing. Although excellent performance was obtained by processing at 850°C, very promising results were achieved at temperatures of only 550°C. If high performance at this low temperature can be achieved, then a considerable cost savings may be realized.

The HEM cells fabricated by ion implantation compare well to the diffused cells fabricated by Hyland et al.,⁽²³⁾ in which performance of 10 to 11% was achieved. We AR-coated 5 cells and achieved an average AM1 efficiency of 12%. With an optimized high efficiency cell process, efficiency of well over 13% should be attainable.

5.4 SEMIX

The results on SEMIX material showed no strong temperature dependence. This is an interesting result when compared to other sheet materials, which did show such sensitivity. The SEMIX material showed high starting diffusion length which was unaffected by thermal processing. We should note that in individual cases higher J_{sc} was obtained after thermal processing, but the average results do not support an argument for the existence of thermal effects.

The results are comparable to those reported in reference 20, which showed efficiency of 12.8% for SEMIX material. We AR-coated three cells and obtained an average efficiency of 11.3%. The cells had good V_{oc} and J_{sc} (553 mV, 31.3 mA/cm²) but had low FF (65.7%) owing to poor metallization. With a reasonable FF of 75%, the cells would have efficiency of up to 13%. With advanced optimized processing, the efficiency would be higher.

5.5 SILSO

The SILSO definitely showed a decrease in both spectral response and J_{sc} after high temperature processing. J_{sc} achieved with PEBA (up to 23.1 mA/cm^2 , no AR) were superior to all J_{sc} achieved with thermal anneals. Low temperature processing would appear to have advantages. Efficiency of 8.34% (no AR-coating) was achieved without exceeding 550°C . As with other sheet materials, considerable economy may be achieved by utilizing low temperature processes. However, an interesting anomaly is the good performance achieved with anneals at 850°C .

Our solar cell performance results are in agreement with Finetti et al.⁽²⁴⁾ who achieved efficiency of 10.5 to 11.5% by both implantation and one-step diffusion. We AR-coated two cells and obtained 11.7% and 12.2%. Presumably, with optimized processing, efficiency of greater than 13% would be achieved. The PEBA-processed cells were found to be quite good, with the average efficiency of 15 cells being 8.29% (no AR-coating). With a 36% gain from AR coating, these cells would have average efficiency of 11.3%. The best PEBA cell would be over 12%.

5.6 SUMMARY OF PROCESSING TEMPERATURE EFFECTS

We consider the J_{sc} obtained by PEBA to be indicative of that which each material can supply prior to thermal processing, and we have normalized the measured J_{sc} for each thermal anneal with the J_{sc} obtained by PEBA. In this way we can contrast temperature effects in the materials under study without recourse to qualifications that usually are invoked when competing technologies must be juxtaposed.

Figures 5-1 and 5-2 summarize the J_{sc} data obtained from one- and two-step anneals. The data presented are averages taken over data presented in Section 4.

The L_D data in Figures 5-1 and 5-2 show several striking effects. Note the increase in J_{sc} that is obtained in FFG as the anneal temperature is increased. In contrast, SILSO and HEM appear to degrade after thermal processing.

FIGURE 5-1. J_{sc} ANALYSIS OF ONE-STEP ANNEAL. The data shown are averages over a small number of cells processed at each temperature.

FIGURE 5-2. J_{sc} ANALYSIS OF TWO-STEP ANNEAL. The data shown are averages over a small number of cells processed at each temperature.

The L_D data that was described in Section 4 has been reduced for one and two step annealing and the result is shown in Figure 5-3A and 5-3B. We have again normalized to the values of L_D obtained from a PEBA-processed cell. The L_D data are in general agreement with Figures 5-1 and 5-2; however, several qualifications are necessary. First, whereas Figures 5-1 and 5-2 are based on average data, Figure 5-3 is based on individual cells having performance as near as possible to the group average. The resultant QE data are believed to be representative. The probable error, however, is difficult to estimate. Second, the QE data were measured without light bias. Light-induced effects have not been considered.

The above qualifications limit us to addressing at best general trends in the L_D data. The CZ data show the large decrease in L_D after processing at 750°C discussed earlier. Also evident is a decrease in CZ diffusion length after annealing at 550°C for 2 hrs. (Figure 5-3A). This decrease is not apparent in Figure 5-3B. Such a result suggests that one-step anneal at 550°C may have been contaminated leading also to degradation in the SEMIX, SILSO and HEM.

Good correlations between J_{sc} and L_D for individual cells made of EFG, HEM and SILSO were not obtained in all cases, owing perhaps to light-enhancement of L_D . In such a case, our concept of an effective diffusion length derived from non-light biased QE data is inadequate. Nevertheless, the data shown in Figure 5-3 do corroborate to a large extent the J_{sc} data and indicate that a base effect is occurring, rather than an effect within the ion implanted emitter.

FIGURE 5-3. EFFECTIVE DIFFUSION LENGTH OBTAINED BY REDUCTION OF THE EXTERNAL QUANTUM EFFICIENCY DATA. (A) One-step anneals. (B) Two-step anneals. The effective diffusion length is normalized to the value obtained with PEBA.

5-8

SECTION 6

CONCLUSIONS AND RECOMMENDATIONS

The data and discussion in the preceding sections indicate that thermal effects are important in most if not all of the polycrystalline sheet materials examined in this work. Although less information was obtained with SEMIX than for the other materials, based on the data obtained, SEMIX appears to be the least sensitive to high temperature processing. EFG appears sensitive to high temperature processes and indeed can benefit by such processes. Based on this investigation, the following general conclusions have been formed.

1. Ion implantation with thermal annealing is a versatile junction formation technique for application to polycrystalline materials. It was shown that cell results compare favorably to diffusion-processing, owing to the freedom to utilize a wide range of temperatures which allows tailoring of the thermal history.
2. Ion implantation with PEBA is a useful technique for low-temperature cell fabrication, with efficiency comparable to thermally-processed cells. Reproducibility must be improved, however.
3. CZ is sensitive to processing at 750°C.
4. Dendritic web is sensitive to long high temperature processes, but the exact reasons have not been determined.
5. EFG appears to benefit from high temperature processing, and thermal anneals may be better than PEBA.
6. HEM shows some sensitivity to high temperature processing, but the best process for junction fabrication is not clear and requires further study.
7. Based on limited data, SEMIX appears to be insensitive to thermal processing.
8. SILSO is sensitive to thermal processing. Low temperature thermal or PEBA processing may be the best process, but more study is needed to determine the sensitivity to processing at 850°C.

Based on these results, the direction for further research is clear. Further work should be devoted to the understanding of the mechanisms occurring during the high temperature processing. The reproducibility of the PEBA process must be improved, although excellent anneal results were obtained on many wafers. More data on SEMIX should be accumulated, and further, low temperature annealing experiments of HEM and SILSO should be carried out. High temperature anneals of EFG may be useful and also should be pursued.

High efficiency processes applied to web appear promising. Although high efficiency was not achieved here, work should continue to investigate application of surface passivation to web.

SECTION 7
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