APPLICATIONS OF ION IMPLANTATION TO HIGH PERFORMANCE, RADIATION TOLERANT SILICON SOLAR CELLS*

Allen R. Kirkpatrick, John A. Minnucci,
and Keith W. Matthei
Spire Corporation

SUMMARY

Ion implanted silicon solar cells have undergone appreciable development during the past two years. Efficiencies now exceed 14 percent AM0 in structures which have not been optimized. Back surface field effects are reproducibly accomplished by implantation. Special annealing in conjunction with implantation has resulted in 0.1 ohm-cm cell open-circuit voltages to 644 mV. Radiation tolerance is being addressed by development of extremely clean processing to avoid contamination-induced defect formation. Very high efficiency cells with good environmental stability characteristics are expected.

INTRODUCTION

For a number of years the potential advantages of ion implantation for fabrication of silicon solar cells have been recognized. To effectively employ implantation to produce high-performance cell structures, a great deal of preliminary work related to damage annealing requirements and profile deficiency corrections has been necessary. Most of this work has now been completed.

At the time of the first High Efficiency Silicon Solar Cell Review in November 1974, silicon cells with efficiencies of 10-11 percent AM0 could be produced. Operational implanters were standard machines used by the semiconductor industry which allowed only marginally satisfactory parameter selections and had poor throughput capabilities at the dose and ion energy levels being utilized. By the Solar Cell High Efficiency and Radiation Damage Meeting in April 1977, efficiency of implanted silicon cells had increased to 12 percent AM0, development of new annealing technology was in progress and profile deficiencies had been recognized (see ref. 1). A modified production implanter was operational at Spire to allow use of improved implant parameters.

Since April 1977, substantial progress has been made. Efficiencies above 14 percent AM0 are now being achieved in implanted spacecraft and terrestrial cell configurations (see ref. 2). Advanced thermal and pulsed-energy-beam transient process annealing techniques are available, as described in references 3, 4 and 5. Much has been learned regarding effective utilization of implant processing. Implanted junctions are still rather deep, typically 0.25 μm or more, and texturized surfaces have not yet been exploited. Inadequacies still exist in the structures of implanted cells. Major improvements remain to be made, but expectations of very high performance can be justified. Solar cell production implantation equipment now exists, and implanters for future high-volume terrestrial cell production have been designed (see ref. 2).

---

*This work is supported in part under NASA Lewis Research Center contracts NAS3-20823 and NAS3-21276.

PRESENT STATUS OF ION IMPLANTED SILICON SOLAR CELLS

One set of implant and thermal anneal parameters is used at Spire for standard processing of most N/P silicon cells with base resistivity of 1 ohm-cm or higher. At present these parameters are as follows:

Junction Implant: 5 keV $^{31}P^+$
$2x10^{15}$ cm^{-2}

Back Surface Implant: 25 keV $^{11}B^+$
$5x10^{15}$ cm^{-2}

Anneal: 550°C - 60 minutes
850°C - 15 minutes
550°C - 60 minutes
In nitrogen

Dopant profiles resulting with these conditions are shown in figure 1. In the past, implant damage annealing was usually performed as a one-step operation at the high temperature needed for electrical activation. Resulting profiles were approximately the same. The two 550°C steps which have been added to the annealing procedure have significant effects upon the performance of resulting cells. The initial 550°C step causes effective epitaxial regrowth of the damaged silicon lattice (see refs. 6 and 7). The final 550°C step is believed to improve minority-carrier lifetime in the silicon bulk.

The listed implantation/anneal conditions now being utilized still result in cell structures which are far from optimized. Using these parameters, efficiencies up to 14.2 percent AM0 are observed in 7.6-cm-diameter cells of 10-ohm-cm (100) silicon. Figure 2 shows performance parameter distributions measured on a group of five hundred 7.6-cm cells prepared using 550/850/550°C annealing (see ref. 8).

DEVELOPMENT IN PROGRESS

Over the past few years the deficiencies of ion implantation for solar cell junction purposes have been corrected. Work is now in progress to improve cell structure, performance and radiation tolerance. Development is being conducted as a number of separate elements which will, as they become available, be later combined to produce highest overall performance and stability. Activities at Spire include:

(i) Development of effective back surface preparation by implantation

(ii) Investigation of junction processing to achieve high V_{oc} in low-resistivity cells

(iii) Investigation of improved radiative tolerance, which may be accomplished by processing with low contaminant introduction.

IMPLANTED BACK SURFACE LAYERS

Although the standard processing now being employed for preparation of ion implanted cells involves implants into both cell surfaces, little has been done toward optimization of the back surface. Examination of the open-circuit voltages of the 10-ohm-cm cells of figure 2 shows that reasonably effective back surface fields are being introduced.

Recently, a test was conducted by OCLI and Spire in which back fields were introduced by $^{11}B^+$ implantation or by aluminum paste alloying into quantities of otherwise identical 10-ohm-cm diffused junction cells (see ref. 9). The implanted-back-layer cells exhibited open-circuit voltages approximately 8 mV lower than those of the aluminum-alloyed-layer cells (average 585 versus 593 mV). Open-circuit voltage distribution of the implanted-back cells was narrower. Very tight V_{oc} distributions are a consistent characteristic of implanted layer cells. The secondary ion mass spectroscopy (SIMS) examinations shown in figure 3 of the alloyed and implanted back layers indicate a deeper and monotonically declining profile from the alloyed aluminum. The implanted boron was apparently inadequately distributed by the processing employed. Correction can be made by direct process variations.

Back layers by implantation have advantages in simplicity and reproducibility. The quality of the implanted surface is substantially better than that of the reprocessed alloyed surface, which should be beneficial for future incorporation of additional back surface optimizations. Figure 4 shows scanning electron microscope (SEM) views of alloyed-aluminum and implanted-boron silicon wafer surfaces. The implanted surface retains its original bright-etch quality.

HIGH OPEN-CIRCUIT VOLTAGE CELLS

It is generally accepted that if high open-circuit voltages approaching 700 mV are to be achieved in cells of low base resistivity, junction characteristics must be improved. Consideration must be given to dopant level and profile, to minority-carrier lifetimes and mobilities and to recombination characteristics of the junction layer surface. Implantation offers the control, reproducibility and flexibility necessary to investigate effects of junction parameter variations upon open-circuit voltage.

Improved open circuit voltages are now being achieved in 0.1-ohm-cm cells with implanted junctions. Figure 5 shows the AM0 I-V characteristic of a 2x2-cm cell with 644-mV V_{oc} at 25°C. Comparable results are easily reproduced.

The implant and anneal parameters employed to prepare the cell of figure 5 were as follows:

Junction Implant: 5 keV $^{31}P^+$
2×10^{15} cm^{-2}

Anneal: 550°C - 2 hours
850°C - 30 minutes
550°C - 2 hours
Oxidizing atmosphere

An oxide grown on the junction layer surface during annealing was left on the cell to serve as surface passivation and as an antireflection coating. The rather modest I_{sc} exhibited in figure 5 is attributed at least in part to the inadequacy of the low-index SiO_2 coating.

Figure 6 shows a SIMS examination of the phosphorus profile produced by the implant and anneal/oxidize conditions listed above. The sharp peak at the immediate surface of the silicon is believed to contribute to the V_{oc} produced.

RADIATION TOLERANT CELLS

It is recognized that radiation tolerance of the silicon solar cell may be limited by radiation-induced defects associated with impurities in the silicon introduced during crystal growth or during device processing. If very high quality silicon, characterized by low content of spurious impurities, is utilized for solar cell fabrication, its quality will be compromised by processing-induced contaminants which cannot be avoided when conventional techniques including thermal procedures are employed. This shortcoming is generally true for ion implantation and thermal annealing. Substantial amounts of carbon and oxygen are known to be introduced by standard implantation procedures (see refs. 10 and 11). However, specialized implantation and energy-beam transient annealing can be combined to fabricate cells with very low introduction of spurious impurities.

In the case of processing by normal implantation, contaminants are introduced by knock-on recoil effects. Incoming ions which impact with surface contaminant atoms can transfer appreciable energy to these atoms, causing them to recoil into the silicon lattice. They may later be redistributed by thermal annealing. The atoms which are introduced in this manner can originate from processing or handling residues, from native oxides and from vacuum system diffusion-pump oil deposits.

Under NASA Contract NAS3-21276, Spire is preparing special processing capability to avoid contaminant introduction. An ion implanter is being modified to replace its process station diffusion pump by a cryogenic pump, to minimize carbon introduction during implantation. The implanter will be operated in a mode in which precleaned wafer surfaces will be in situ sputter-cleaned immediately prior to dopant introduction. Transient annealing by pulsed electron beam and pulsed laser methods (see refs. 3, 4 and 5) under clean environmental conditions will be used to anneal implant damage without thermal elevation of the silicon bulk. It is expected that C and O atom introduction by this processing will be reduced approximately four orders of magnitude from existing levels.

Some preliminary testing of silicon solar cells fabricated by good implantation and annealing techniques prior to preparation of the special capabilities described above has shown promise of improved radiation tolerance (see ref. 12). Controlled preparation of cells from silicon of best available quality may result in substantial improvements.

PLANNED DEVELOPMENT

Present activities will soon cause the efficiency of ion implanted silicon cells to rise above 15 percent AM0 and could provide capability for achieving improved radiation tolerance. During the next phase of development of ion implanted cells, total device optimization will have to be addressed. Most of the requirements can now be defined. Among the needed component elements are the following:

- Higher open-circuit voltages by optimization of implantation and anneal procedures
- Higher current densities by use of texturized front surfaces and advanced back layer structures
- Further reduction of contaminant levels and of structural imperfections by improved utilization of transient processing methods

REFERENCES

1. Minnucci, J. A.; and Kirkpatrick, A. R.: Proceedings of Solar Cell High Efficiency and Radiation Damage Conference. Lewis Research Center, April 1977, p. 99.

2. Kirkpatrick, A. R.; Minnucci, J. A.; Greenwald, A. C.; and Josephs, R. H.: Proceedings of 13th IEEE Photovoltaic Specialists Conference. Washington, June 1978, p. 706.

3. Greenwald, A. C.; Little, R. G.; and Minnucci: J. A., IEEE Trans. Nucl. Sci. NS-26(1), 1683 (1979).

4. Greenwald, A. C.; Kirkpatrick, A. R.; Little, R. G.; and Minnucci, J. A. J. Appl. Phys. 50(2), 783 (1979).

5. Greenwald, A. C.; and Little, R. G. Solid State Tech. 22(4), 143 (1979).

6. Csepregi, L.; Mayer, J. W.; and Sigmon, T. W. Appl. Lett. 29(2), 92 (1976).

7. Csepregi, L.; Shu, W. K.; Muller, H.; Mayer, J. W.; and Sigmon, T. W.; Radiat. Eff. 28, 227 (1976).

8. Cells fabricated for delivery to Jet Propulsion Laboratory under LSA Project Contract 954786.

9. Minnucci, J. A.; Kirkpatrick, A. R.; Iles, P. A.; and Khemthong, S.: Presentation at Electrochemical Society Meeting, Boston, 8 May 1979.

10. Moline, R. A.; and Cullis, A. G. Appl. Phys. Lett. 26(10), 551 (1975).

11. Tsai, M. Y.; Streetman, B. G.; Blattner, R. J.; and Evans, C. A. J. Electrochem. Soc. 126(1), 98 (1979).

12. Drevinsky, P. J.; Schott, J. T.; DeAngelis, H. M.; Kirkpatrick, A. R.; and Minnucci, J. A.: Proceedings of 13th IEEE Photovoltaic Specialists Conference. Washington, June 1978.

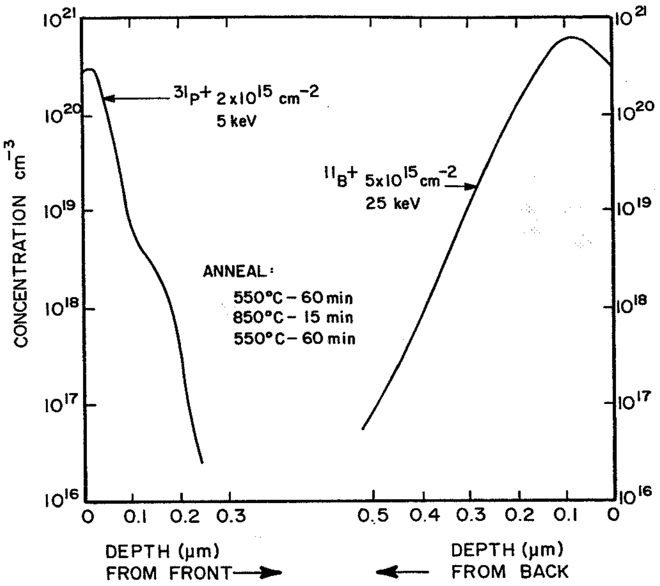


FIGURE 1. MEASURED DOPANT PROFILES FROM STANDARD IMPLANT/ANNEAL CONDITIONS

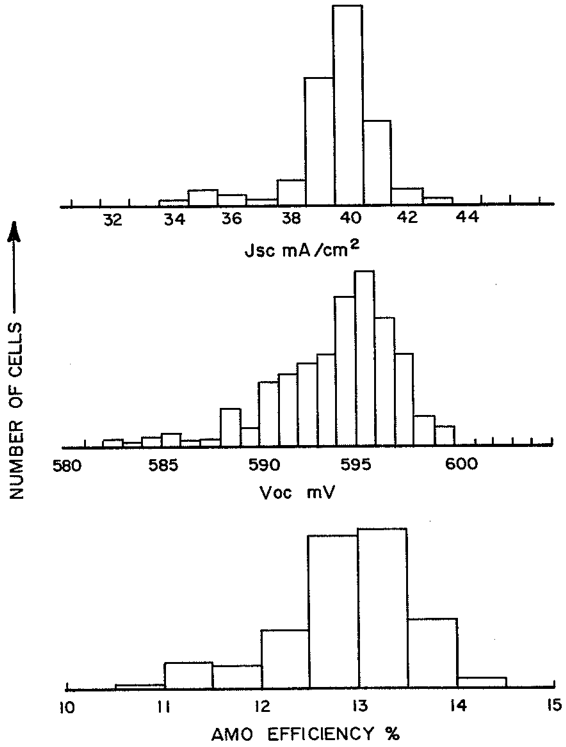


FIGURE 2. 25°C AMO PERFORMANCE DISTRIBUTIONS OF 500 IMPLANTED N^+PP^+ 3-INCH CELLS

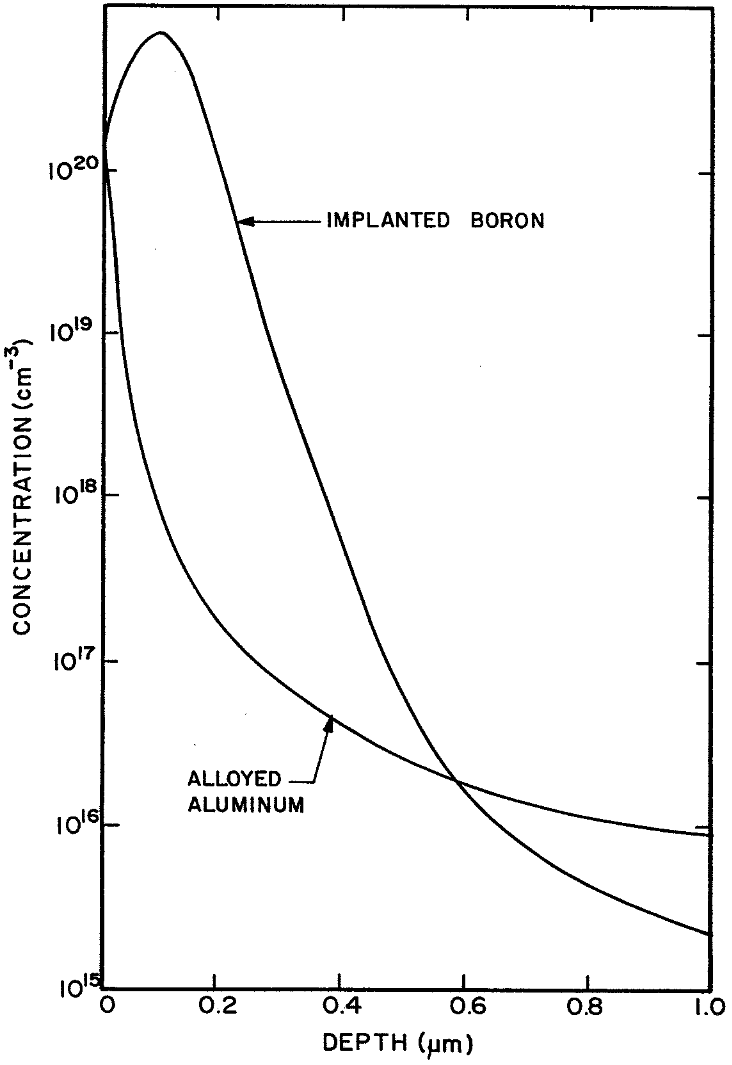
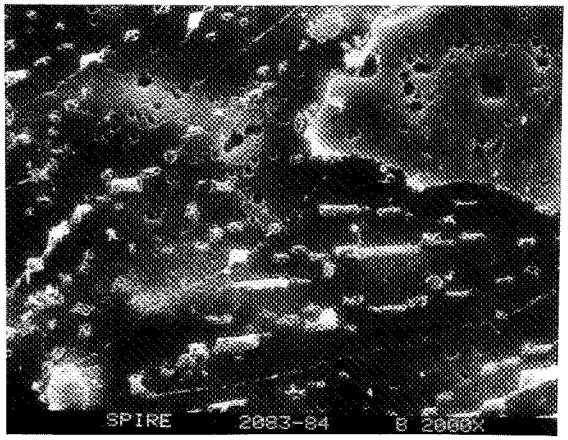
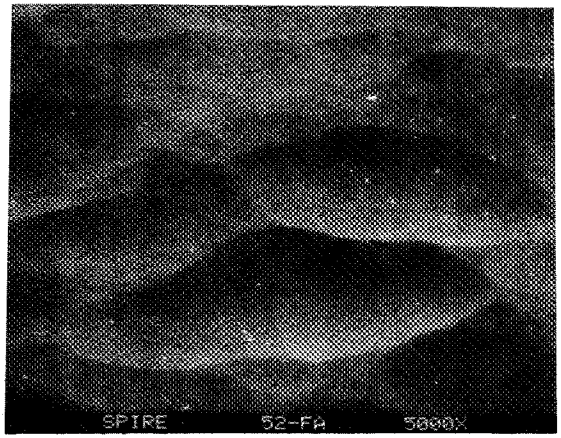


FIGURE 3. BACK LAYER PROFILES DETERMINED BY SIMS



(A) Back Surface After Thick-Film Aluminum Alloy (2,000X)



(B) Back Surface After Ion Implantation and Furnace Anneal (5,000X)

FIGURE 4. SEM MICROGRAPHS OF TWO BSF PROCESSED SURFACES

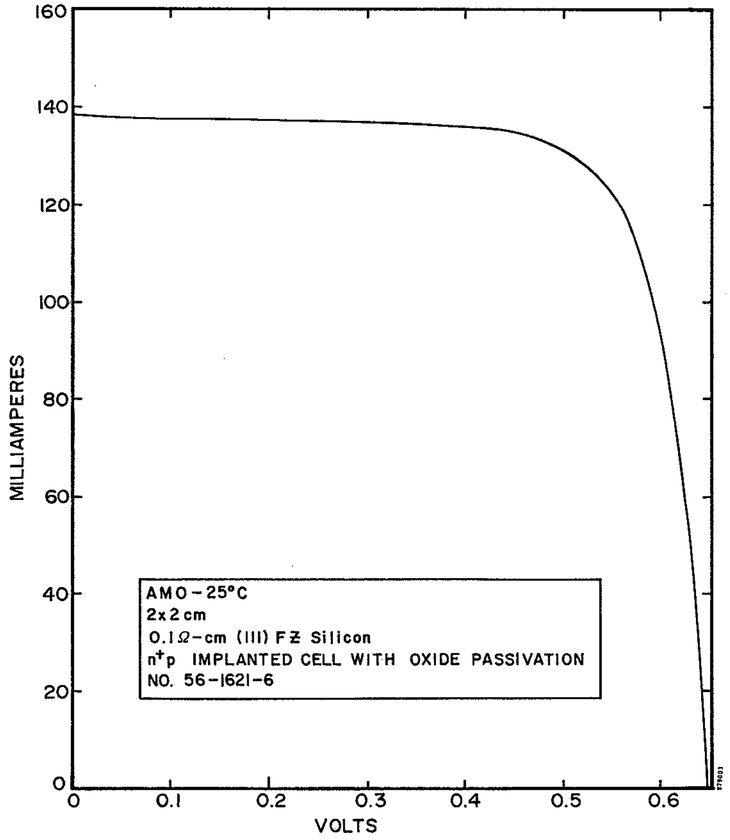


FIGURE 5. AM0 I-V CHARACTERISTIC OF HIGH V_{oc} CELL

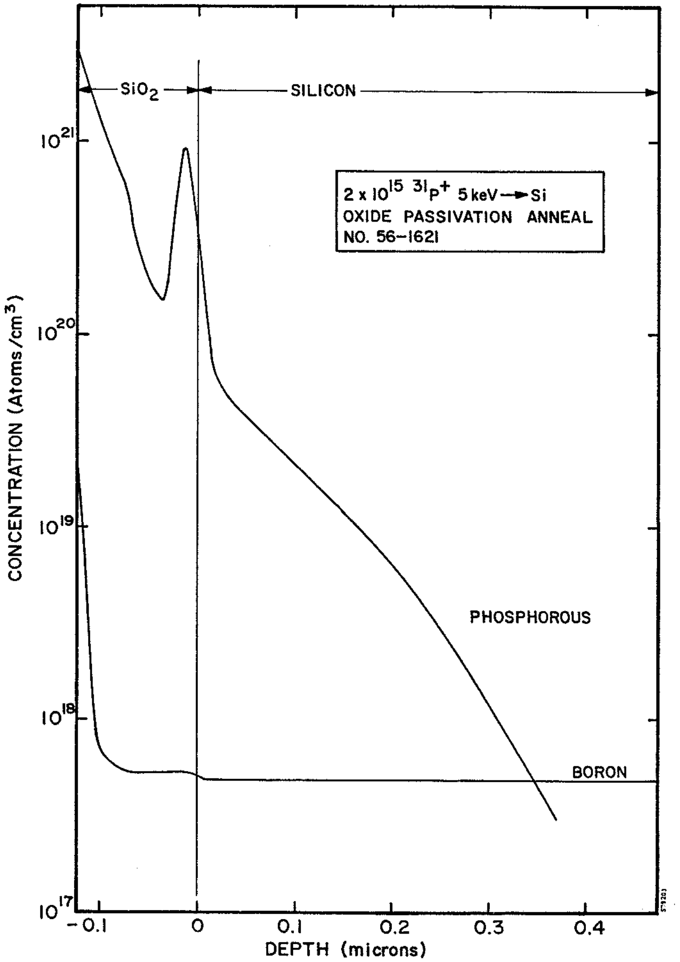


FIGURE 6. SIMS PROFILE OF PHOSPHORUS IN IMPLANTED CELL WITH PASSIVATING OXIDE