ION IMPLANTATION PROCESSING FOR HIGH PERFORMANCE CONCENTRATOR SOLAR CELLS AND CELL ASSEMBLIES

P. R. YOUNGER and S. N. BUNKER

Spire Corporation, Bedford, MA 01730 (U.S.A.)

(Received May 29, 1981; accepted October 1, 1981)

Summary

The present status of ion implantation processing for high performance concentrator solar cells is reported. Implantation parameters and conditions for both thermal and pulse electron beam annealing are reviewed. Production cell current–voltage characteristics and distributions are given. Peak performance reaches 18%. Development efforts for performance enhancement techniques such as surface passivation and implantation gettering are discussed. Finally, line focus cell assembly design features are presented.

1. Introduction

High performance ion implantation processing is now being used routinely to fabricate both line and point focus concentrator solar cells. Thermal treatment at present provides the best method of implant annealing, while pulse electron beam annealing offers both technical and cost advantages for the future. Total fabrication sequences have been developed and are available for volume manufacturing of concentrator cells.

Ion implantation offers technical, economic and environmental advantages that make it an attractive high volume manufacturing technique for solar cells. Technical advantages include high cell efficiency with the narrowest performance distribution, total process reproducibility and virtually 100% process yield. A high production rate, negligible materials usage and low energy consumption are cost benefits. Elimination of post-process wet chemistry and end-product waste makes implantation an environmentally attractive process.

Efficiencies of large area (12.5 cm^2) line and point focus cells exceed 17% at 50 °C under a 25 sun concentration. Production cells, used in line focus cell assemblies, average 16% under similar test conditions. High concentration cells with efficiencies above 17.5% under 50 suns have been developed.

0379-6787/82/0000-0000/$02.75

2. Ion implantation cell processing

Phosphorus and boron implants are used to form the n^+-p-p^- structure shown in Fig. 1. The cell material is low resistivity float zone silicon which is chosen rather than Czochralski silicon because float zone silicon has a higher lifetime. Resistivity, varying between 0.3 and 1.0 Ω cm, is selected on the basis of the application. Wafers with a (100) orientation are preferred because of more favorable annealing than (111).

Implantation parameters now being used for production cells are as follows: junction implant, 2.5×10^{15} $^{31}P^+$ cm^{-2} at 5 - 10 keV; back-surface implant, 5.0×10^{15} $^{11}B^+$ cm^{-2} at 25 keV. After the samples had been thermally annealed in dry nitrogen, the dopant profiles obtained from them are similar to those shown in Fig. 2. The front-junction depth is approximately 0.25 μm. Implantation of boron into the cell back does not disturb the wafer surface morphology, so that effective aluminum back-surface reflectors can be introduced by low temperature processing.

Present production processing procedures employ multistep thermal annealing to remove radiation damage from implanted regions of the lattice. Pulse electron beam annealing has been developed to the point where cell efficiencies nearly equal those obtained by thermal annealing. This process will be used in future large-scale production lines. Prototype high volume in-line implantation and pulse annealing equipment is being developed [1].

Standard thermal annealing developed for flat-plate cells [2] and now being applied to concentrator cells consists of the following three steps performed in dry nitrogen: 120 min at 550 °C; 15 min at 850 °C; 120 min at 550 °C.

The initial 550 °C step causes epitaxial regrowth of the damaged silicon lattice. Different cycles are required for wafers of other orientations because of vastly different regrowth rates, especially for Si(111) [3]. After crystallinity has been restored, dopant activation takes place at 850 °C. Process parameters and procedures are most important for this step, since the minor dopant redistribution that takes place at this time can significantly enhance performance. The final low temperature step is used to enhance minority carrier lifetime.

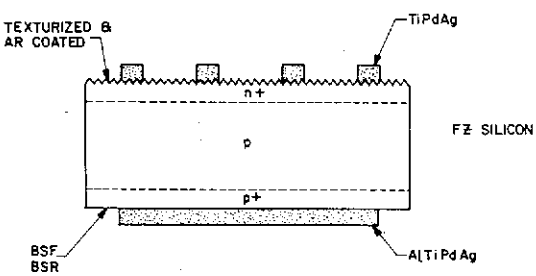

Fig. 1. Texturized and antireflection (AR) coated back-surface field (BSF)–back-surface reflector (BSR) concentrator cell structure (FZ, float zone).

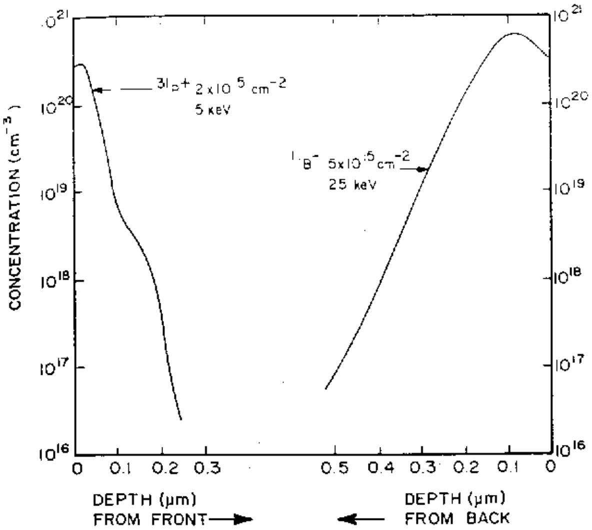

Fig. 2. Dopant profile for standard implant–anneal conditions (60 min at 550 °C, 15 min at 850 °C and 60 min at 550 °C).

While these procedures are effective in producing high performance concentrator cells, they are neither optimized for maximum production throughout nor ideal for all resistivity ranges. Shortening of both 550 °C steps is possible without loss of performance, and some combination of the steps is possible.

For the maximum production rate required for high volume manufacture, pulse electron beam annealing can effectively combine and shorten these process steps. In particular, a single pulse of 10^{-7} s duration can simultaneously produce liquid phase epitaxial regrowth and dopant activation. The cell performance, nearly equivalent to that produced by thermal annealing, is limited primarily by the lack of a lifetime enhancement step. Active development efforts are aimed at the incorporation of this function into the pulse annealing process.

In addition to increased throughput, pulsed electron beam annealing has technical advantages that offer a potentially better concentrator cell performance than thermal annealing. Sheet resistances typical of thermally annealed phosphorus implants are 50 - 60 Ω/□. Pulse electron beam annealing of phosphorus generally yields sheet resistances of 30 - 40 Ω/□. Pulse annealing, which momentarily melts the wafer surface, apparently provides more complete dopant activation. For boron implants this effect is more pronounced. Typical thermal annealing of 10 Ω cm material yields 100 Ω/□ while pulse annealing has achieved 13 Ω/□ [4].

While refinements in pulse annealing are required to achieve cell efficiencies equal to those of thermal annealing, the availability of greater dopant activation and lower sheet resistances is important for concentrator cells which are subject to an illumination of many suns and which produce high currents.

Additional features of standard concentrator cells include texturized surfaces for increased light collection, fine-line metallization grids produced by vacuum deposition of Ti–Pd–Ag contacts and electroplating to increase current-carrying capacity. Standard cell metallization patterns have been optimized to minimize the combined losses from conductor resistance, contact resistance and active area shadowing. The computer program used for this optimization is capable of including the non-uniform illumination typical of most optical concentrators as a variable. In this way, the cell grid pattern is matched to the particular optical system.

Standard production cells for moderate concentration are now being routinely produced with an average efficiency exceeding 17% at 28 °C and 25 sun illumination. Peak efficiencies of 18% are achieved. Typical cell characteristics under these conditions are an open-circuit voltage V_{oc} of 660 mV, a short-circuit current density J_{sc} of 0.87 A cm^{-2}, a fill factor FF of 75.4%, an efficiency η of 17.3% and an output power density of 0.433 W cm^{-2}.

When cells are operated in concentrator system receivers, their temperature reaches at least 50 °C. Accordingly, cells are tested and matched at that temperature before being incorporated into the cell assemblies discussed below. Figure 3 shows the current–voltage (I–V) curve of a single line focus concentrator cell measuring 2.5 cm × 5.0 cm. This cell has an efficiency of

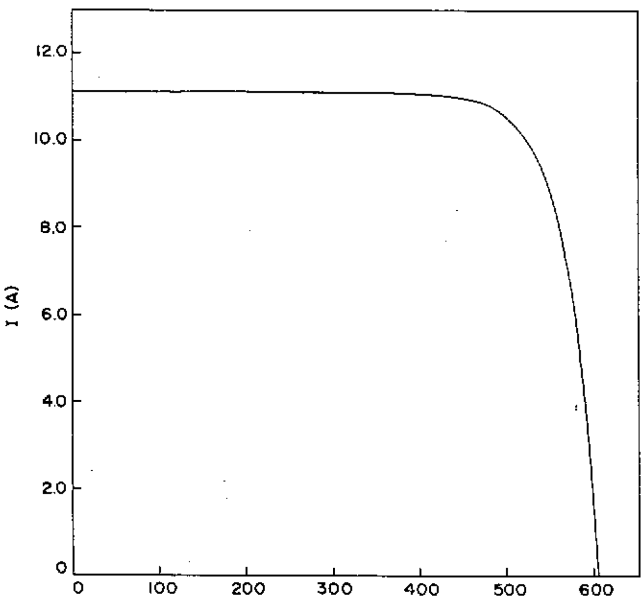

Fig. 3. I–V curve of Spire 12.5 cm^2 line focus concentrator cell (η = 17.0%; illumination, 25 suns; temperature, 50 °C).

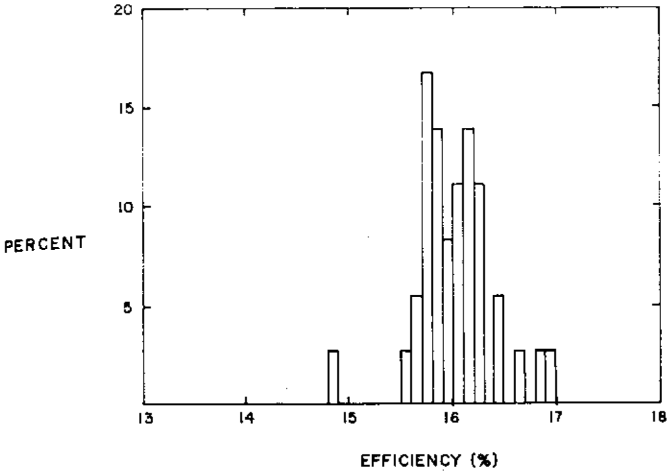

Fig. 4. Performance distribution of Spire 12.5 cm^2 line focus concentrator cells (illumination, 25 suns; temperature, 50 °C; mean efficiency, 15.967%; standard deviation in efficiency, 0.381%; 36 data points).

17% at 50 °C under 25 suns. It was part of the production lot whose performance distribution is shown in Fig. 4. The average cell efficiency under elevated temperature (50 °C) operating conditions is 16% with a standard deviation of 0.38% efficiency or 2.4% of output power. The narrowness of this performance spread is of particular value to manufacturers of concentrator systems, since the cell assemblies generally consist of rows of individual cells connected in series. Within each of these series strings, performance is determined by the average value. Cells of a greater output operate at voltages above their peak power point and thus at less than maximum output, while cells of lesser output operate at reduced voltages and in the worst cases go into reverse bias. Tight performance distributions are valuable in maintaining peak efficiency.

Low resistivity cells (0.3 Ω cm) have been fabricated for extended concentration range applications. Peak cell efficiencies approach 18% at 25 °C under 50 suns, with efficiency still increasing. Tests at higher concentration ranges are currently in progress. The performance under varying concentration for both low and medium resistivity cells is shown in Fig. 5.

Developments not yet integrated into the production sequence for concentrator cells offer potential for significant performance improvement. Carrier recombination at the cell front surface can greatly reduce output. This is particularly important in heavily metallized concentrator cells. A quantitative evaluation of this effect was made by the removal of a portion of the current collector ring from a point focus concentrator cell. This removal reduced overall metallization coverage from 25% to 10% and resulted in a 37 mV increase in open-circuit voltage. After this test a new cell was designed in which the collector ring was isolated from the silicon by a thermally grown surface-passivating oxide.

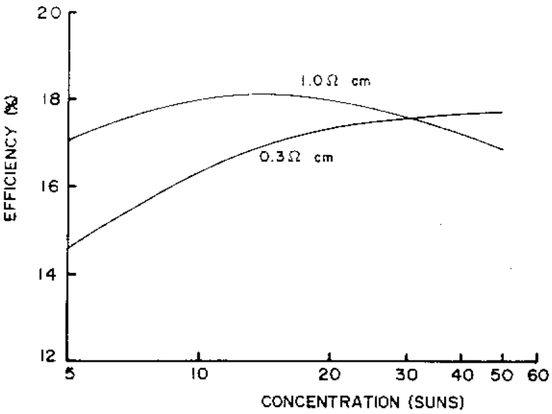

Fig. 5. Efficiency *vs.* concentration for low and medium resistivity concentrator cells.

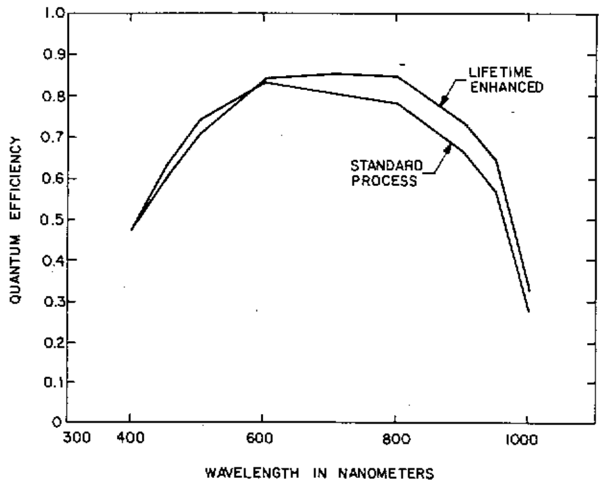

Fig. 6. Spectral response of lifetime-enhanced and non-enhanced float zone silicon solar cells.

Lifetime enhancement through phosphorus implantation has been evaluated. 10 Ω cm (111) wafers were implanted with 5×10^{15} $^{31}P^{+}$ at 25 keV and annealed at 950 °C in nitrogen. After removal of the implanted layer, standard implant cell processing was applied. Under 1 sun illumination these cells showed 30 mV increases in open-circuit voltage and 6.6 mA cm^{-2} increases in short-circuit current when compared with non-gettered controls. The effect on cell spectral response is shown in Fig. 6.

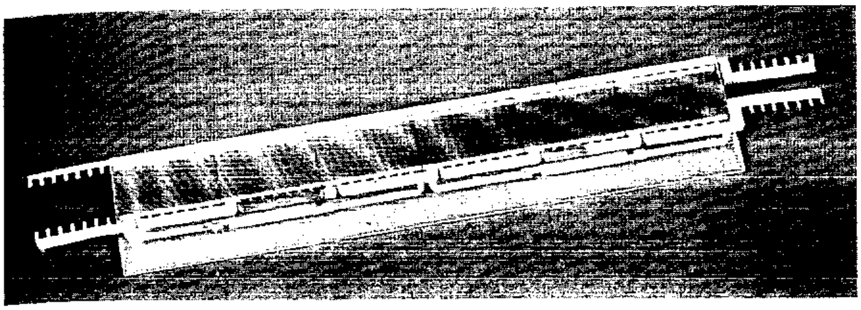

Fig. 7. Line focus concentrator cell assembly.

3. Cell assembly design

Line focus production cells of the type discussed above have been incorporated into high reliability cell assemblies for both actively and passively cooled receivers. Cells measuring 5.08 cm in length and 2.8 cm in width and having an active area of 12.5 cm^2 are connected in series with a spacing of 0.75 mm. This close spacing, achieved by simple fixturing and uniform encapsulation processing, is essential for high module efficiency. Multiple-tab copper interconnectors run along each side of the cells and contact cell fronts and backs at a density of 2 points cm^{-1} of cell length. This high number of small tabs minimizes the stress potential at solder joints. Low leakage bypass diodes are connected across each group of three series-connected cells to provide circuit protection.

Circuits containing six or more cells are laminated to tempered low iron glass superstrates with ethylene–vinyl acetate (EVA) encapsulant. Figure 7 shows one of these finished cell assemblies. EVA is preferred over poly(vinyl butyral) because it is a lower modulus material that will prevent the build-up of excessive thermomechanical stress when the mounted cell assembly is subjected to temperature cycling during field operation. Thermal tests of EVA-encapsulated assemblies have shown no failure or bubbling of the encapsulant up to the melting point of the soldered interconnects (180 °C). This basic structure has undergone extensive accelerated testing in flat-plate modules without failure [5].

4. Conclusions

Ion implantation has been demonstrated to be a high performance, low cost manufacturing process for concentrator solar cells. Its many advantages include precise process reproducibility, tight performance distributions, 100% process yield, high production rate, low energy and materials consumption and elimination of wet chemistry processing and end-product wastes.

At present, cells designed for moderate concentration range are made from 1.0 Ω cm float zone silicon. The average efficiency of production cells exceeds 17.5% at 25 suns (25 °C) with a performance spread of 0.4% efficiency. Low resistivity (0.3 Ω cm) cells for an extended concentration range have been tested to 50 suns with efficiencies approaching 18% at 25 °C and still increasing.

Advanced processing techniques for performance enhancement have been identified. These include surface passivation and implantation gettering. These effects have produced performance increases of up to 20% at 1 sun. Incorporation of these procedures into standard processing is expected to enhance the performance of production concentrator cells significantly.

Cell assemblies incorporating ion implanted cells have been designed, fabricated and tested. Features include low iron glass covers, low modulus encapsulant, bypass diodes, redundant stress relief interconnects and close cell spacing for high module efficiency.

References

1 G. A. Landis, A. J. Armini, A. C. Greenwald and R. A. Kiesling, *Proc. 15th Photovoltaic Specialists' Conf., Orlando, FL, May 1981*, IEEE, New York, 1981.

2 A. R. Kirkpatrick, J. A. Minnucci and A. C. Greenwald, *Proc. 14th Photovoltaic Specialists' Conf., San Diego, CA, January 7 - 10, 1980*, IEEE, New York, 1980, p. 820.

3 T. W. Sigman, *IEEE Trans. Nucl. Sci., 28* (1981) 1767.

4 Silicon concentrator solar cell development, *Final Rep. 10068*, 1980 (Spire Corporation, Bedford, MA) (Sandia Contract 13-3548).

5 Design, fabrication, test, qualification and price analysis of third generation design solar cell modules, *Final Rep. 10063*, 1980 (Spire Corporation, Bedford, MA) (U.S. Department of Energy–Jet Propulsion Laboratory Contract 955405).