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# Combined thermal diffusion – ion implantation fabrication processing for silicon solar cells

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*Combined fabrication technology utilises the advantages of both thermal diffusion and ion implantation. Thermal gas phase diffusion of phosphorous results in a high quality emitter. Ion implantation as a doping process for back p-p⁺ barrier formation can be technically optimal and economically effective, despite the costlier nature of ion implantation. Some of the distinct advantages of ion implantation are: controllability, doping uniformity, reproducibility, elimination of some high temperature operations such as protective oxide growth and several wet stages. As a result, the fabrication process is significantly simpler and should provide higher yields, probably at a lower cost, to which the contribution of the ion implantation stage is estimated as 11–13 cents/W. Initially, combined thermal diffusion-ion implantation technology was developed at KVANT for space cell production. Different types of solar cells have been designed, produced and successfully used for the space program: transparent, infrared reflective, bifacial and high resistivity silicon solar cells. Processing has since been improved for application for terrestrial cell fabrication. Samples of terrestrial cells with relatively thick (0.5–0.7 μm) passivated low doped emitters demonstrate close to 100% collection of carriers generated by short wavelength light. Internal quantum efficiency in the long wavelength range is very high when solar cells are made from FZ silicon and appreciably lower when the starting material is multicrystalline silicon. Bifacial structures fabricated on FZ substrates by improved processing have a current symmetry factor of 0.7–0.9, which is due to retention of the bulk diffusion length at a level of 600–900 μm. The bifacial structure on multicrystalline substrates is much less effective due to low bulk diffusion length (~130 μm).*

**Keywords:** solar cells, silicon, fabrication technology, ion implantation, bifacial cells.

## 1. Introduction

Present industrial fabrication of silicon solar cells is based on thermal diffusion as a doping process, in which vapour or solid sources of the desired impurities are used. The alternative solar cell fabrication technology based on ion implantation as a method of introducing a doping impurity has been comprehensively investigated [1–3]. Use of this doping method in the semiconductor industry has increased dramatically in recent years (see, for example Ref. 4). However, the application of ion implantation processing for solar cell production is very limited. Just a few publications are dedicated to silicon solar cell industrial production using ion implantation procedure [5–8], and only one of them [5] discusses the industrial fabrication technology with doping completely based on ion implantation operations. In the other references ion implantation doping is a part of a combined thermal diffusion-ion implantation technology. Open tube doping by thermal diffusion of phosphorous is used for emitter preparation, and doping by boron ion implantation for p-p⁺ barrier formation. Such combined technology was first developed by KVANT for fabrication of the space solar cell [6], and later by Spectrolab, Inc., USA, for the same applications [7,8].

The limited use of the ion implantation technique in a silicon solar cell industry can be attributed to two reasons. One is the high level of development of thermal diffusion processing with fine doping controllability, high production rate and high yield. The second is the seemingly costly nature of the ion implantation operation.

Industrial solar cell production by the combined thermal diffusion-ion implantation technology demonstrates the opportunity of satisfying of a wide range of requirements of the solar cell [6,9,10]. Laboratory experiments show the possibility of improving this processing, which can be relatively cheap, simple and combine the advantages of both doping methods.

The advantage of using the combination of thermal diffusion and ion implantation in the frame of a unified production technology is demonstrated here. Improvements of this process will also be discussed.

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## 2. Achievements of combined industrial fabrication processing

The general requirements for solar cell fabrication processing can be formulated as follows:

- simplicity, high yield, low cost,
- high cell efficiency,
- adaptability to multipurpose cell applications,
- suitability for different silicon materials.

These requirements can be met by combined thermal diffusion-ion implantation fabrication processing. The technology, first developed by KVANT, unified the advantages of both doping methods for preparing $n^+$-p-$p^+$ structures. Thermal diffusion, in particular gas phase diffusion, with $POCl_3$ as the source for $n^+$-p junction formation results in a proven controllable quality of $n^+$-p junctions. The ion implantation process is very controllable and reproducible. The required quantity of boron doping atoms can be precisely introduced into the silicon wafer. ILU-4 implantors with conveyer transportation of wafers and a pass-through wafer loading system are used for industrial solar cell production. Boron ions, accelerated to energy of 30 keV, bombard the wafer with a spatial uniformity better than ±10% over a surface 10×10 cm. The ion dose rate can be varied in the range of $10^{11}$–$5\times10^{14}$ ions/cm$^2$s.

Low temperature thermal processing (below 950°C) which includes the phosphorous deposition procedure and simultaneous defect annealing, and drive in of the dopants (boron and phosphorous) facilitate the preservation of bulk lifetime of carriers.

The combination of several stages in the unified procedure decreases the number of operations. There is no need for a protective layer for the opposite side of the wafer, so that same stages, i.e. high temperature oxidation and subsequent oxide etch are not needed in the fabrication procedure. This also results in shortening and simplifying the fabrication process. As a result, the production technology requires less energy consumption for thermal stages and less chemical consumption for the wet operations. These advantages overcompensate for the extra cost of the implantation process, which, according to analysis of production expenses, is in the range of 11–13 cent/W, depending on dose of implanted ions.

Different types of solar cell can be fabricated using the combined processing. Among them there are the following:

- **Conventional low-resistivity silicon solar cells.** The main positive results of the $n^+$-p-$p^+$ structure fabricated by this combined technology are low resistance of the back contact and decrease of losses due to back surface recombination. These cells are used on a variety of space missions.
- **High resistivity silicon solar cells (solar cells with p-i-n structure).** Increased resistance to the space radiation environment was achieved by using ~25 Ω cm silicon as a starting material for solar cell production [11,12]. The first industrial production and application for space missions of high resistivity silicon solar cells was undertaken by KVANT after adjustment of the combined processing procedure for this type of silicon. Cells of this type are usable for environments with intermediate equivalent fluences of space radiation.
- **Bifacial solar cells.** Bifacial silicon solar cells with an $n^+$-p-$p^+$ structure, which were first described in Ref. 13, were fabricated by KVANT [14,15] and used for space missions. Industrial production of such cells is possible due to the combined thermal diffusion-ion implantation technology. The results achieved using bifacial cells on low altitude missions are illustrated in Fig. 1. Load currents of bifacial and conventional solar panels on the Salut 5 space station at 350 km altitude are shown here [14,15]. Additional power generated by the bifacial panel, due to conversion of earth albedo, is on average ~17% and achieves 50% when the earth's surface is covered by clouds. The average additional power could exceed 25% for improved bifacial cells and solar array designs.
- **Solar cells with modified reflectance and transmittance.** The combined fabrication technology can control the optical and thermal properties of solar cells. Cells were designed to be transparent or reflective for long wavelength light with photon energies lower than the silicon energy gap. The goal achieved by these developments is a decrease of the equilibrium working temperature as a result of lower solar light absorption, and a corresponding increase of generated power.

Data on light absorption as a function of wavelength, measured for different types of solar cells fabricated by the combined technology are shown in Fig. 2 [10]. Curve 1 shows conventional solar cells with a ground back com-

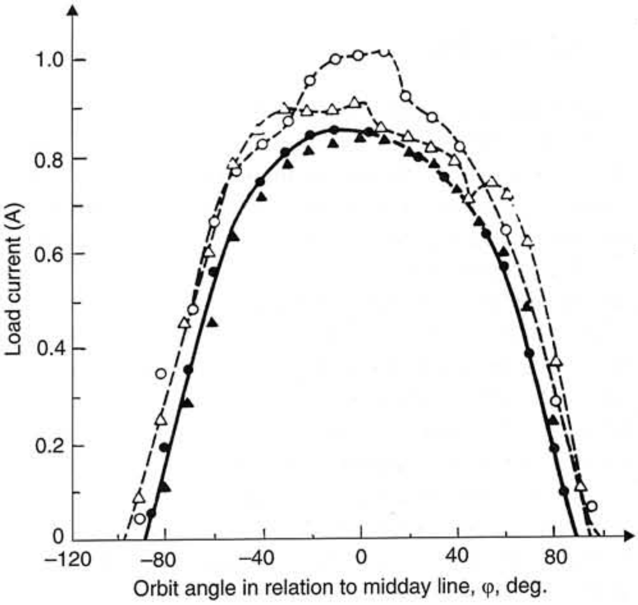

Fig. 1. Current of conventional (•,▲) and bifacial (O,Δ) solar arrays of the Salut-5 space station as a function of angular position in orbit. Different symbols indicate data measured during different revolutions.

Table 1. Optical, thermal and power parameters of silicon solar cells with decreased solar absorptance.

| Type of solar cell | Solar absorptance | Emittance | | Equilibrium temperature (°C) | Power enhancement (ΔP/P)×100% |
|---|---|---|---|---|---|
| | | Front | Back | | |
| Non-polished back | 0.87 | 0.81 | 0.90 | 53 | 0 |
| Polished back completely covered by Ti-Pd-Ag layer | 0.82 | 0.81 | 0.90 | 47 | 3 |
| Transparent | 0.71 | 0.81 | 0.81 | 38 | 7.5 |
| Reflective | 0.74 | 0.81 | 0.90 | 38 | 7.5 |

pletely covered by a regular Ti-Pd-Ag contact. No significant change of absorption with wavelength, to 1.1 μm, is observed. Curve 2 shows the same cell design, but having a polished back. Some decrease in absorption in the infrared region is due to reflection by the back contact. However, the reflectance of the Ti-Pd-Ag film on silicon is not very high. Curve 3 is the absorption function of a solar cell transparent to infrared light with photon energy lower than the silicon energy gap. Absorption of light with wavelengths over ~3 μm is attributed to glass absorption. Somewhat higher absorption is measured for a reflective cell (curve 4). The polished back of this cell is covered with a Ti-Pd-Ag grid and an Al reflective layer covers the remaining back area. The values of solar absorptance, $\alpha_s$, of transparent and reflective solar cells, are significantly lower than $\alpha_s$ of conventional cells. Use of transparent and reflective modifications of the silicon solar cell decreased the working temperature of space solar arrays by up to 15°C, depending on satellite altitude and array design with a corresponding increase of power generated by the solar array. Table 1 summarises the thermal effects and performance enhancement of transparent and reflective cells on a high altitude space mission.

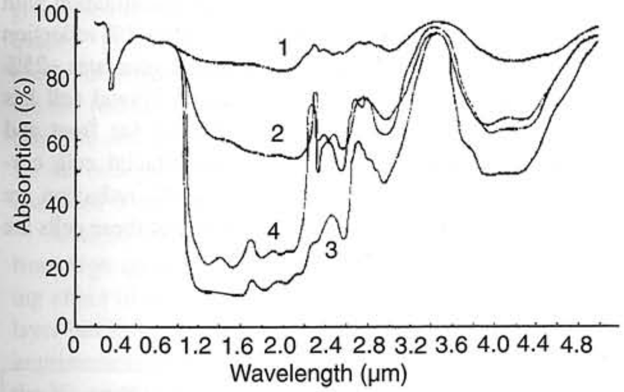

Fig. 2. Spectral dependence of solar cells absorptance: 1 – conventional cell with nonpolished back completely covered by Ti-Pd-Ag contact and front antireflective coated and glass covered; 2 – the same design with a polished back; 3 – transparent cell with both sides polished, and with contact grids, antiflective coated and glass covered on the front and back; 4 – reflective solar cell as in #2, but with a back Ti-Pd-Ag contact grid and Al mirror layer completely covering the back.

## 3. Improvement of the combined technology process for solar cell fabrication

Experiments to improve the combined fabrication technology were initiated to achieve better solar cell performance and to adapt it for the fabrication of terrestrial cells. The laboratory fabrication procedure is depicted in Fig. 3. Neither wafer texturisation nor antireflective coating depositions are included in the processing. Processing is quite simple; no oxidation stages for growing a protective oxide and no oxide or silicon etching operation.

Experiments were conducted using two types of starting p-silicon. One, FZ single crystal mirror polished wafers, 270 μm thick, orientation (100) with resistivity 22–80 Ω cm; and the second, Bayer Solar GmbH multicrystalline

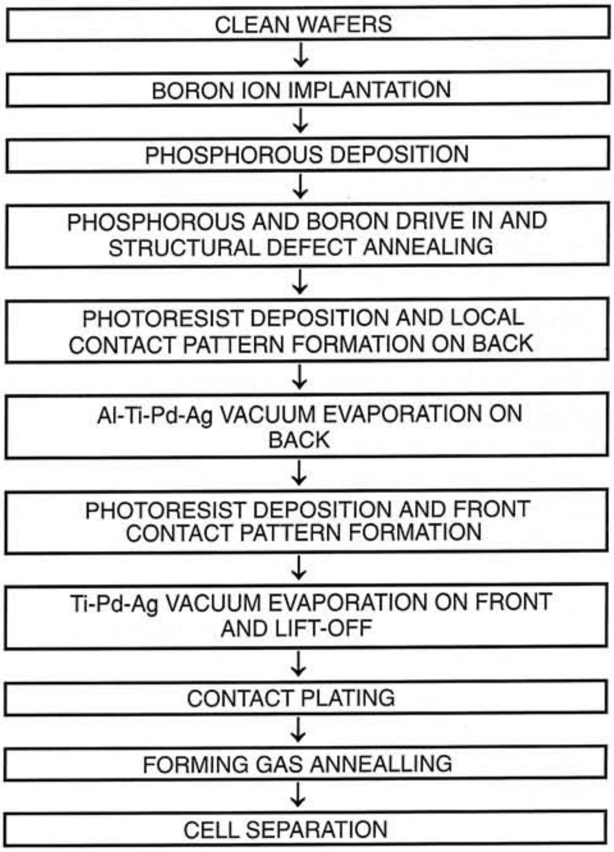

Fig. 3. Combined thermal diffusion-ion implantation fabrication process sequence.

wafers, 0.5–2.0 Ω cm with a thickness of 260–280 µm. Their final treatment is acid polish etch.

Emitter-doping was carried out by gas phase phosphorous diffusion using $POCl_3$ as a source. The deposition stage was 840°C for 25 min. The drive-in stage was combined with the defect annealing stage.

For boron ion implantation with energy 30 keV, the above industrial system was used. The desirable dose of boron ions and annealing conditions were chosen based on experimentally determined dependencies of electrical properties of the $p^+$ doped layer as a function of implanted dose and annealing temperature. The sheet resistance of the implanted layer, surface concentration of ionised impurities and portion of implanted ions in electrically active states are among these parameters. As an example, the sheet resistance of a $p^+$ layer as a function of annealing temperature is shown in Fig. 4, with the implanted dose as a parameter.

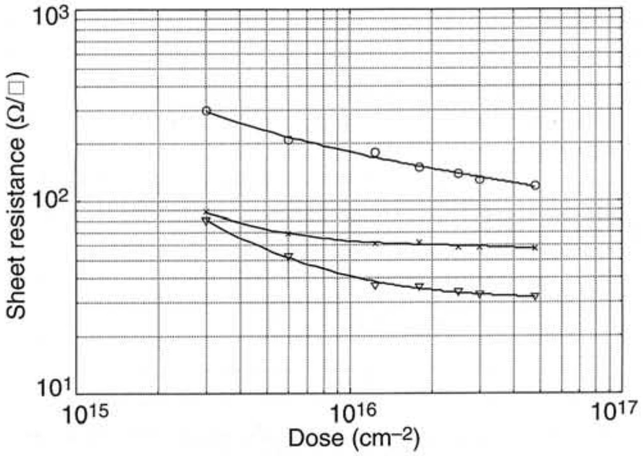

Fig. 4. Sheet resistance of $p^+$ layers versus implanted boron ion dose after annealing for 30 min at different temperatures: 850°C (o), 900°C (x), 950°C (∇). Ion energy E = 30 keV.

Doses of $(0.8–1.25)\times10^{16}$ ions/$cm^2$ were used for the first experiments. 950°C was chosen as the temperature of the annealing stage to provide complete transfer of the boron impurity atoms to electrically active states and for maximum structural defect annealing.

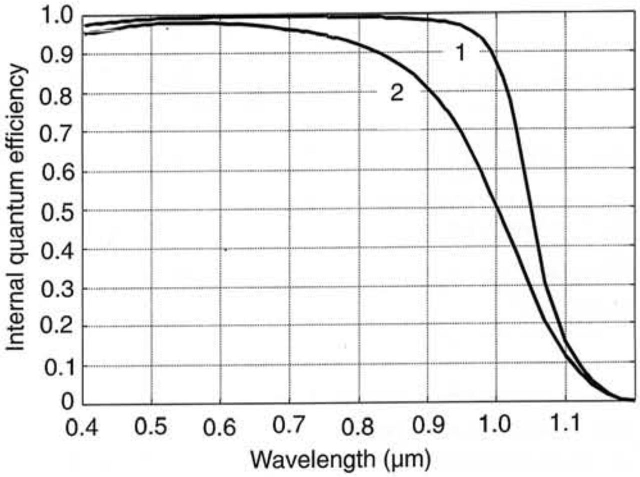

Fig. 5. Internal quantum efficiency of single crystal solar cells #25-4-2 (1) and multicrystalline solar cells #Poly 1-7-2 (2).

Phosphorous draw-in occurs also during the annealing stage. The resulting profiles of phosphorous distribution in the emitter are characterised by a depth of 0.6 ±0.1 µm and a surface concentration $(2–7)\times10^{19}$ $cm^{-3}$. Thin passivated layers of silicon dioxide results in a surface recombination velocity $\leq10^{-3}$ cm/s. The resulting internal quantum efficiency (IQE) in the short wavelength range indicates that emitter recombination parameters are good. This is true for both types of silicon used, single crystal and multicrystalline (curves 1 and 2, correspondingly, in Fig. 5).

Long wavelength (IQE) of single crystal and multicrystalline solar cells differ, reflecting the difference of effective carrier diffusion lengths, $L_b$, in the base region of these cells. High IQE of single crystal cells at $\lambda > 0.8$ µm indicates retention of bulk lifetime during the fabrication procedure. The $L_b$ value of the multicrystalline cell is only ~130 µm.

The cells, IQE of which are shown in Fig. 5, are bifacial cells with contact grids on the back. The multicrystalline sample parameters for front illumination are: short circuit current density, $J_{sc}$ = 31 mA/$cm^2$, open circuit voltage, $V_{oc}$ ≈595 mV for AM 1.5, 1000 W/$m^2$ solar illumination with correction for an anti-reflective coating with 7% reflection of sunlight. For back illumination this cell generates ~25% of front $J_{sc}$ due to small $L_b$. The single crystal cell has better and more symmetrical performance for front and back illumination. I-V curves for this bifacial cell, corrected for an antireflective coating with 7% reflection are shown in Fig. 6. Parameters of I-V curves of these cells are summarised in Table 2.

Table 2. Parameters of the solar cell # 25-4-2 with 100 mW/$cm^2$ illumination.

| | Short circuit current density (mA/$cm^2$) | Open ccircuit voltage (mV) | Fill factor | Efficiency (%) |
|---|---|---|---|---|
| Front illumination | 37 | 616 | 0.79 | 18 |
| Back illumination | 28.5 | 607 | 0.79 | 13.7 |

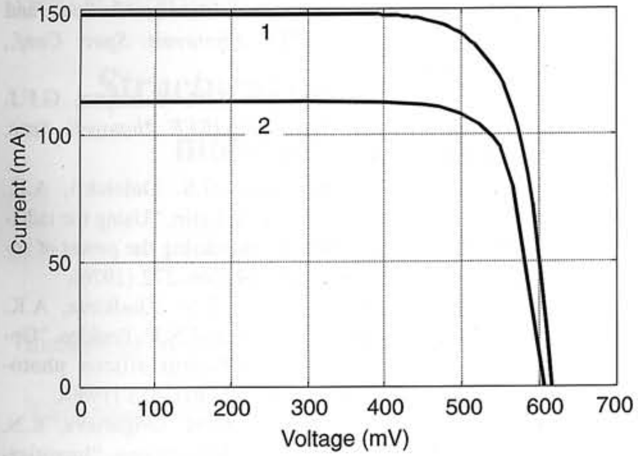

Fig. 6. I-V curves of a bifacial single crystal cell #25-4-2. (Boron ion implantation dose $1.25\times10^{16}$ ions/cm$^2$. 1 – front illumination, 2 – back illumination.

## 4. Discussion

### 4.1. Efficiency-limiting factors

As shown by the initial experiments presented above, the combined technology process is desirable for fabrication of high efficient silicon solar cells with simple $n^+$-p-$p^+$ structures. The direction for further solar cell improvement depends on the starting solar cell material. However, some general remarks can be made.

The quality of the emitter of experimental cells is high enough to provide its maximum contribution to the photocurrent irrespective of type of starting silicon (see Fig. 4). Fabrication processing retains the bulk lifetime of FZ single crystalline silicon. The implanted $p^+$ layer suppresses the effective surface recombination on the back of a cell. Therefore the contribution of the base region to current generation is also close to the maximum for a given silicon quality. Therefore, the photocurrent can be increased by optical improvements in the cell design. Among them there are the following: surface texturing, deposition of a more effective antireflective coating, use of a back reflector (not for the bifacial or transparent cells). Photocurrents can be increased 6–8% by the above-mentioned improvements.

Analysis of recombination losses in the cells, fabricated from high quality, high resistivity silicon shows the limiting effect of the $p^+$ layer on the $V_{oc}$. The structure of this layer has to be optimised. According to PC 1D modelling, improvement of implanted layer parameters could increase the $V_{oc}$ to 630–650 mV.

### 4.2. Economic factors

Advantages of combined thermal diffusion-ion implantation fabrication technology are shown by the industrial production of space silicon solar cells. Simple fabrication procedures and high yield make this technology very attractive for terrestrial cell production. Evaluation of the expenses for the ion implantation operation in the cell fabrication procedure (11–13 cent/W) correlates with published data on the economics of ion implantation in the semiconductor industry. For example, implantation of boron ions of very high energy (400 keV) is only ~ twice as expensive as the above [4]. Target area enlargement, use of lower acceleration energy (15 keV or less) and improvement of the conveyer wafer loading system should decrease the cost of implantation operation by a factor of ≥ 3. Even the current cost of the ion implantation stage does not exceed ~10% of the optimistic lower future cost of a silicon solar cell [16].

The cost of the ion implantation operation is overcompensated by elimination of some operations from the technology procedure and by reducing energy and chemical consumption (it is worthwhile to mention that the laboratory fabrication procedure depicted in Fig. 3 can be reduced very easily by unifying stages of the photoresist deposition and contact evaporation on both sides of a wafer). The second cost-compensating factor is an increase in the yield of high quality cells. The third cost-compensating factor is the multipurpose character of the combined process, suitable for fabrication of solar cells for a wide range of specifications. An example of the usefulness of this technology for terrestrial cell production, is in its suitability for fabrication of bifacial cells. Interest in terrestrial application of these cells is growing because of the opportunity of increasing the photovoltaic energy generation without increasing cell area [6].

## 5. Conclusions

The combined thermal diffusion-ion implantation technology is used for the industrial production of different types of space solar cells with simple $n^+$-p-$p^+$ structures: conventional low resistivity silicon cells, high resistivity silicon cells, bifacial cells, transparent and reflective cells. The wide application of these cells on space missions is evidence of the advantages of this fabrication technology.

Processing has been improved for application to terrestrial cell fabrication. The improved technology provides very high internal quantum efficiency at short wavelengths in both single crystal and multicrystalline cells. The technology procedure also provides retention of bulk lifetime in FZ silicon. Bifacial solar cells fabricated on single crystalline silicon have quite good performance for front and back illumination.

The efficiency-limiting factors of the cells fabricated by improved processing are nonoptimal optical design and recombination losses in the $p^+$ layer.

A simple fabrication procedure and high yield make the combined technology process very attractive for terrestrial cell production. The current cost of the ion implantation operation, 11–13 cent/W, can be significantly decreased. Moreover, ion implantation expenses are overcompensated by a decreased number of operations, lower energy and chemical consumption and high yield.

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