



# Aluminum alloy back p–n junction dendritic web silicon solar cell

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## Abstract

A new silicon solar cell structure is presented in which the p–n junction is formed by alloying aluminum with n-type silicon, and where this p–n junction is located at the back (unilluminated) side of the cell. With a phosphorus front diffusion, the resultant  $n^+np^+$  structure has been implemented using dendritic web silicon substrates which are 100  $\mu\text{m}$  thick and doped with antimony to 20  $\Omega\text{cm}$ . Such a structure eliminates shunting of the p–n junction, provides an effective front surface field, enables a high minority carrier lifetime in the base, and is immune to light-induced degradation. Using only production-worthy, high-throughput processes, aluminum alloy back junction dendritic web cells have been fabricated with efficiencies up to 14.2% and with corresponding minority carrier (hole) lifetime in the base of 115  $\mu\text{s}$ . © 2001 Elsevier Science B.V. All rights reserved.

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## 1. Introduction

Silicon substrates of sufficiently high quality that minority carrier diffusion length exceeds the substrate thickness lend themselves to non-conventional solar cell structures. Dendritic web silicon ribbon, which can be grown quite naturally at a thickness of 100  $\mu\text{m}$ , is such a substrate. A solar cell structure designed to exploit this property is illustrated in Fig. 1. The most striking feature of this cell is the aluminum alloy p–n

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## PHOSTOP Cell

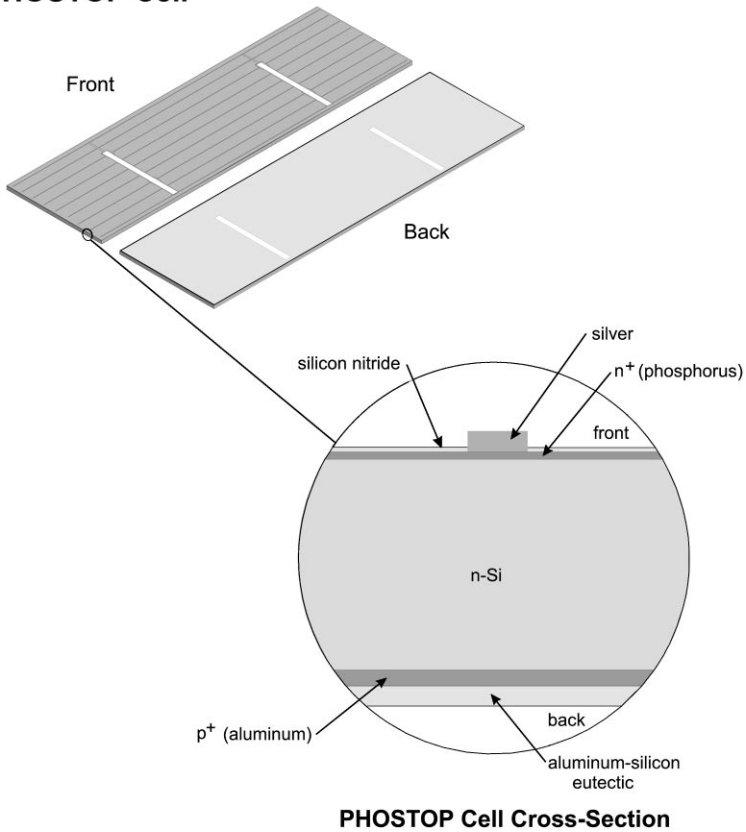


Fig. 1. Structure of aluminum alloy back-junction silicon solar cell.

junction at the back (unilluminated) side. The substrate is doped lightly with antimony in order to ensure a high minority carrier (hole) diffusion length. A phosphorus-doped layer, which gives rise to a strong electric field for effectively passivating the front surface, leads to an  $n^+np^+$  structure. With a silicon nitride anti-reflective (AR) coating and solderable silver contacts as a grid on the front and as two stripes over the aluminum–silicon eutectic metal on the back, the cell is complete. This cell has been named “PhosTop” because the top surface is doped with phosphorus rather than boron, as is usually the case for an n-base cell.

A comparison of a conventional silicon cell with the dendritic web silicon PhosTop cell is given in Table 1. There are several potential advantages of the PhosTop cell over the conventional cell. First, shunting of the p–n junction is eliminated. The junction is formed by alloying aluminum with n-type silicon to form a  $p^+n$  structure. The aluminum–silicon eutectic remains as a self-aligned metal to contact the  $p^+$  surface. Aluminum cannot shunt the p–n junction because aluminum creates a junction when it contacts silicon. Moving the p–n junction from the front of the cell

Table 1

Conventional silicon cell versus dendritic web silicon “PhosTop” cell

Cell feature	Conventional cell	Dendritic web “PhosTop” cell
Substrate thickness	300 $\mu\text{m}$	100 $\mu\text{m}$
Substrate type (dopant)	p-type (B)	n-type (Sb)
Substrate resistivity	1 $\Omega\text{ cm}$	20 $\Omega\text{ cm}$
Junction (dopants)	$\text{n}^+\text{p}$ (P, B)	$\text{p}^+\text{n}$ (Al, Sb)
Junction location	Front ( $\text{n}^+\text{pp}^+$ )	Back ( $\text{n}^+\text{np}^+$ )

to the back opens the possibility of making the front diffused layer thinner without the risk of shunting. The prospect of enhancing the blue response of cells in this way was recognized previously for cells with a  $\text{p}^+\text{pn}^+$  structure fabricated from 100  $\mu\text{m}$  thick wafers sawn from a three-grain ingot [1].

A second advantage of the PhosTop cell is the existence of a strong front surface field. This arises from the phosphorus-diffused layer on the lightly doped n-type substrate which creates a strong electric field. The recombination velocity of minority carrier holes at the front  $\text{n}^+\text{n}$  junction is, therefore, quite low. A previous study of such an  $\text{n}^+\text{n}$  junction in a dendritic web silicon cell concluded that the effective recombination velocity must be  $< 100\text{ cm/s}$  at the  $\text{n}^+\text{n}$  junction, with a value of 25 cm/s at the maximum power point deduced [2].

The dendritic web silicon PhosTop cell holds a third potential advantage over the conventional cell in its high lifetime for minority carriers in the base. Light substrate doping (20  $\Omega\text{ cm}$ ) reduces the recombination activity associated with electrically-active defects in the material by virtue of the location of the Fermi level near the center of the bandgap [3]. The choice of n-type is also important because minority carrier holes carry a positive charge. The principal defect in dendritic web silicon is an oxide precipitate decorating a dislocation core. The surface of such an oxide precipitate is expected to have a positive charge, which would repel holes from the defect but attract electrons. Lifetime degradation associated with oxygen precipitates has been observed to be much more severe in p-type silicon than in n-type [4]. Thus, the choice of n-type dopant having low concentration ensures a large minority carrier diffusion length for typical dendritic web silicon crystals.

A final advantage of the PhosTop cell is that there is no light-induced degradation since it has an n-type base. Conventional cells using Czochralski-grown wafers doped with boron to 1  $\Omega\text{ cm}$  exhibit a stabilized 4% drop in  $V_{\text{oc}}$  after exposure to one-sun illumination for only 6 h [5]. This degradation has been traced to the existence of boron–oxygen pairs [6]. Since PhosTop substrates have no boron they are free from light-induced degradation.

## 2. Experimental results

The PhosTop cell of Fig. 1 was fabricated from dendritic web silicon substrates nominally 100  $\mu\text{m}$  thick and doped with antimony to 20  $\Omega\text{ cm}$ . Only simple,

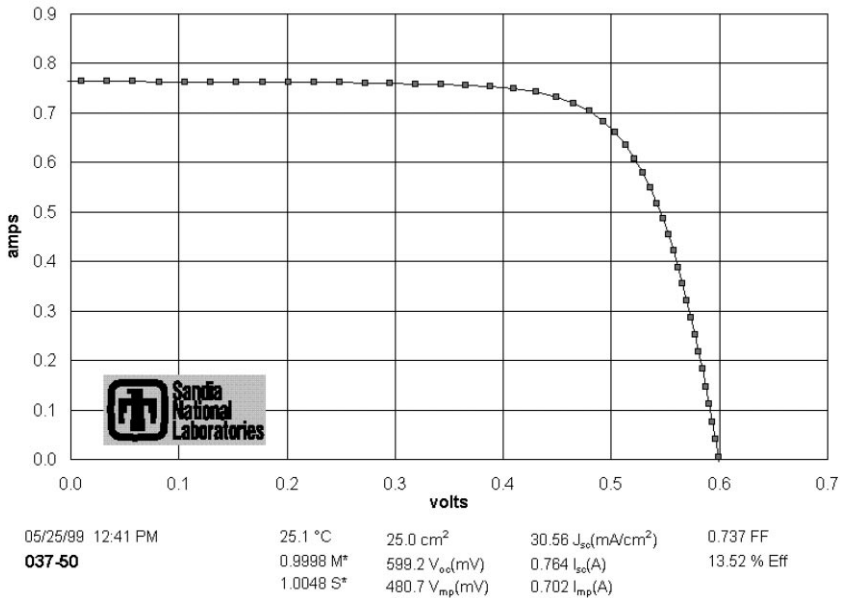


Fig. 2. Lighted  $I$ - $V$  data for  $n^+np^+$  aluminum alloy back-junction solar cell (PhosTop037-50), 25 cm<sup>2</sup> in area. Cell fabricated from a dendritic web silicon substrate (100  $\mu$ m thick, antimony-doped to 20  $\Omega$  cm), with phosphorus RTP diffusion, screen-printed aluminum and silver, and PECVD silicon nitride AR coating. Measured one-sun efficiency is 13.5%, with  $J_{sc}$  of 30.6 mA/cm<sup>2</sup>,  $V_{oc}$  of 0.599 V, and FF of 0.737.

high-throughput processes, thought to be compatible with a production environment, were used. The front surface field ( $n^+n$ ) was created by applying a phosphorus liquid dopant followed by diffusion in a rapid thermal processing (RTP) unit or in a radiantly heated belt furnace to approximately 40  $\Omega/\square$ . The back junction ( $p^+n$ ) was formed by screen-printing aluminum, then alloying the aluminum with silicon in a belt furnace. Silicon nitride was deposited on the front by plasma-enhanced chemical vapor deposition (PECVD) as an anti-reflective coating. Finally, solderable contacts in the form of a grid on the front and two stripes on the back aluminum-silicon eutectic metal were created by screen-printing silver and firing in a belt furnace.

The lighted  $I$ - $V$  curve, as measured at Sandia National Laboratories, for a dendritic web silicon PhosTop cell 2.5 cm  $\times$  10.0 cm in size is given in Fig. 2. An efficiency of 13.5% was obtained. In such a cell, the screen-printed aluminum is held back from the edge of the silicon by 0.5 mm in order to avoid direct contact with the  $n^+$  layer on the front. Spectral data taken with a 1-sun light bias for the same cell are given in Fig. 3. The location of the  $p$ - $n$  junction at the back of the cell is clearly indicated by the positive slope of the internal quantum efficiency (IQE) curve over its central portion. The reflectivity from the front surface is fairly high, with a weighted value of 13.0% for the global spectrum. This represents a loss of 2.0% (absolute) in efficiency.

Some PhosTop cells were made using a screen with a more efficient front grid pattern. In this case the dendritic web silicon cells were diced out at the end of the

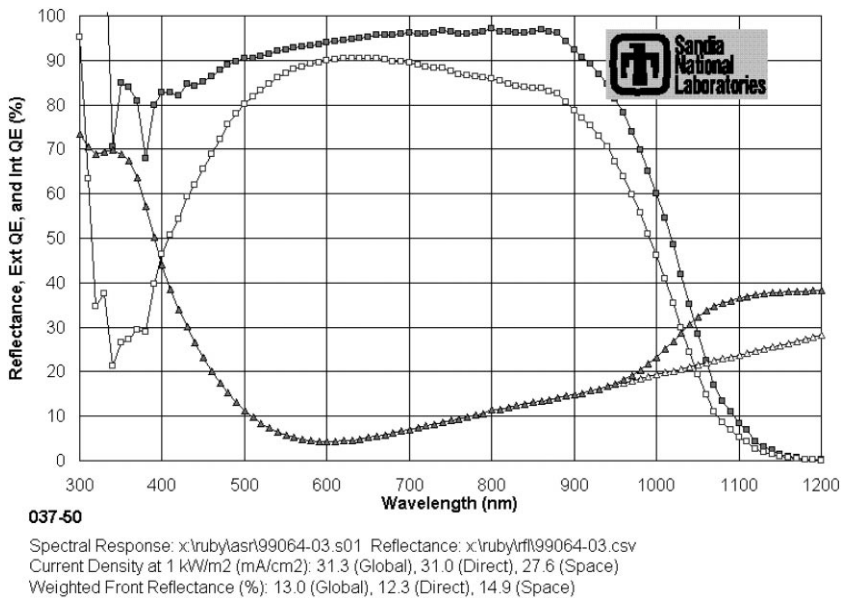


Fig. 3. Spectral data taken with a one-sun white light bias for 13.5% aluminum alloy back-junction silicon solar cell (PhosTop037-50) fabricated from 100  $\mu\text{m}$  thick dendritic web silicon. Note the internal quantum efficiency curve (solid squares) has a positive slope over the range of 500–850 nm, indicating the p–n junction is at the back of the cell. Note also a weighted front reflectance of 13.0% (global).

process to a size of 2.0 cm  $\times$  2.0 cm so that the entire back surface was covered with metal (no 0.5 mm border). In this case cell efficiencies up to 14.2% were realized, with  $J_{\text{sc}}$  of 31.0 mA/cm<sup>2</sup>,  $V_{\text{oc}}$  of 0.606 V, and FF of 0.756 (Sandia measurements). Spectral data for this cell are given in Fig. 4. An estimate of the minority carrier (hole) lifetime in the base was obtained by fitting the IQE curve using PC-1D. This gave a value of 115  $\mu\text{s}$ , equivalent to a hole diffusion length of 370  $\mu\text{m}$  which significantly exceeds the 100  $\mu\text{m}$  substrate thickness.

### 3. Discussion

Efforts are underway to boost the efficiency beyond 14% demonstrated for dendritic web PhosTop cells to date. Values of  $V_{\text{oc}}$  and FF are usually quite acceptable, but  $J_{\text{sc}}$  is lower than desired. This is largely because a significant amount of light is lost to reflection, and because the blue response of the cell is relatively poor. Methods of texturing the (1 1 1) surface of dendritic web silicon are being explored to reduce reflection losses. Efforts to improve blue response are aimed at reducing the phosphorus doping concentration near the front surface. This may require a more sophisticated surface passivation scheme and a modification of the front metallization process to retain low-resistance ohmic contacts.

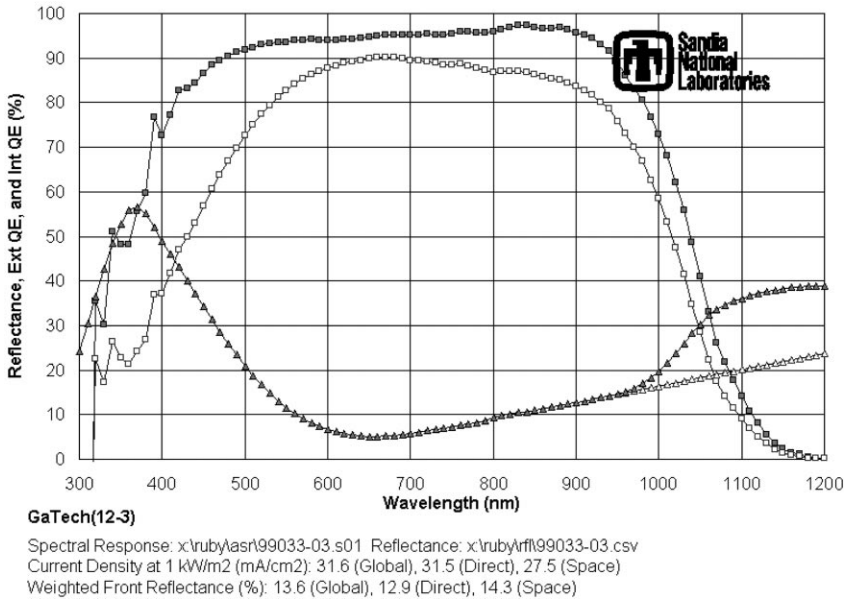


Fig. 4. Measured spectral data for 14.2% aluminum alloy back-junction solar cell (12-3) fabricated from 100  $\mu\text{m}$  thick dendritic web silicon. Cell area is 4.0  $\text{cm}^2$ , with  $J_{\text{sc}}$  of 31.0  $\text{mA}/\text{cm}^2$ ,  $V_{\text{oc}}$  of 0.606 V, and FF of 0.756. Fitting the IQE curve required a hole lifetime of 115  $\mu\text{s}$  (diffusion length of 370  $\mu\text{m}$ ).

It may also be desirable to segment the back aluminum in some fashion. This would reduce the consumption of aluminum paste and would also alleviate the bowing that sometimes occurs because of the mismatch in thermal expansion coefficient between aluminum and silicon. Preliminary attempts to reduce the back aluminum coverage have shown that even modest openings in the aluminum cause a severe reduction in cell performance. It is clear that the exposed silicon must be passivated in some way. Promising approaches include thermal oxide, deposited dielectric layers, and a light diffusion with boron or phosphorus. If an effective method for passivating the exposed back silicon is found, then the front metal contact could be moved to the back in an interdigitated back contact configuration. Such an approach not only eliminates grid shadowing, but also enables simpler methods to interconnect cells.

#### 4. Conclusions

From this work the following conclusions can be drawn:

1. The quality, uniformity, and reproducibility of aluminum alloy p-n junctions are satisfactory for silicon solar cells;
2. A high-throughput, low-cost process utilizing screen-printing and belt furnace diffusion, alloying, and firing can be applied to 100  $\mu\text{m}$  thick dendritic web silicon substrates with acceptable yield;

3. Cell efficiency in excess of 14% and minority carrier lifetime in excess of 100  $\mu\text{s}$  can be achieved with the PhosTop cell structure using dendritic web silicon substrates (100  $\mu\text{m}$  thick, antimony-doped to 20  $\Omega\text{cm}$ ) and high-throughput processes.

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