BACKSIDE-CONTACT SILICON SOLAR CELLS WITH IMPROVED EFFICIENCY FOR THE ’96 WORLD SOLAR CHALLENGE

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ABSTRACT: This paper reports on recent improvements in the fabrication of Backside-Contact silicon solar cells for high-value applications such as solar race cars and airplanes. A study of the losses limiting the efficiency of the cell indicated that the most limiting factor is the carrier recombination at the saw-cut perimeter of the die. This loss mechanism has been simulated and the results have suggested a reduction in the substrate resistivity. The paper reports on the cell design and manufacturing for the ’96 World Solar Challenge. The efficiency of the cells ranged from 20 to 23.2% (AM1.5, 25°C) which represents a boost of one absolute percentage point above the efficiencies obtained in ’93. The same cell independently measured demonstrated a AM0 efficiency of 20.3%, which shows that the Backside -Contact cell is one of the most suitable cells for solar airplane applications.

Keywords: High-efficiency - 1: Silicon - 2: Backside-Contact - 3

1. INTRODUCTION

The races of solar cars and the development of high-altitude unmanned solar-powered airplanes have been excellent opportunities and incentives for increasing the efficiency of solar cells, and for demonstrating the manufacturability and the reliability of such cells. The most prestigious solar car race of all, the World Solar Challenge, is a 3000 km race across Australia, from Darwin to Adelaide, and is reserved to cars or bicycles entirely powered by the energy of the sun. SunPower’s Backside-Contact solar cells, of which a cross section is drawn in Figure 1, were used to power “Dream”, the solar car designed by Honda which won the 1993 World Solar Challenge. This was the first time that Backside-Contact silicon solar cells were used for a non-concentration application, and also the first time that a significant volume of Backside-Contact solar cells were produced and tested for reliability [1-2].

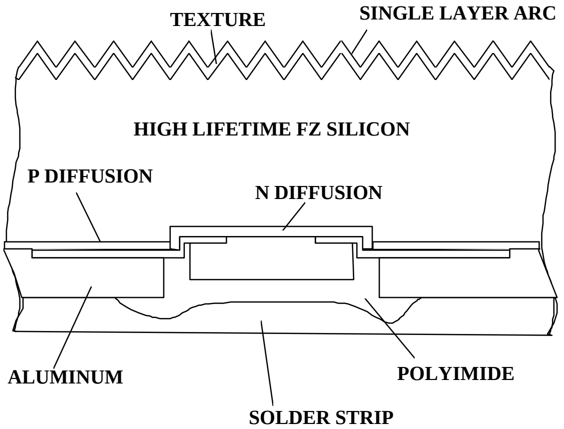

Fig. 1: Cross section of a Backside-Contact solar cell.

The cells made for “Dream” for the ’93 World Solar Challenge were produced in a time period of 4 months and averaged 21.1% efficiency under AM1.5, 25°C conditions. The efficiency distribution proved to be very tight, ranging from 20% to 22%. The reliability of the Backside-Contact cell was demonstrated during the ’93 World Solar Challenge since none of the cells encapsulated into the modules failed. Several cells from this same production run were also used in fabricating a world-record 21.6%-efficient flat-plate module with an area of 862 cm^2 [3].

The purpose of this paper is to describe the improvements made on the design of Backside-Contact cell for the ’96 World Solar Challenge. The improvements leaded to an increase in efficiency by one absolute percentage point, up to 23%. Unfortunately, the Backside-Contact cells did not have the chance to demonstrate their performance during the race this time. The ’96 World Solar Challenge was won by Honda again, but the car was primarily powered with very high efficiency PERL cells fabricated by the University of New South Wales (UNSW) [5] with a very small fraction of SunPower cells. The Team California car, 50%-powered by SunPower’s Backside-Contact solar cells, was built by a team of students from Stanford and Berkeley Universities and had many power electronics problems during the race.

In this paper, we will present and discuss the improvements made to the cell design, and report on the manufacturing of the cells and the efficiency results.

2. EFFICIENCY IMPROVEMENTS

The best demonstrated one-sun silicon solar cell to date has a reported efficiency of 24% [6]. This result obviously represents a goal for the manufacturing of large-volume production solar cells, even if the comparison is somewhat difficult due to the fact that the above result is for a small area (4 cm^2) cell that is not diced from the wafer before testing, and therefore does not have any edge loss. The ’93 Backside-Contact cell was 22% efficient, showing a 8.4% relative loss in efficiency compared to the best cell to date. An extensive analysis of the loss mechanisms limiting the efficiency of the Backside-Contact solar cells compared to the maximum theoretical efficiency has been performed [4]. We concluded that the largest loss in efficiency is due to edge recombination, i.e. the loss of photogenerated current and/or voltage due to the recombination of carriers at the saw-cut edge of the cell. We simulated the cell behavior with and without edge losses and concluded that the Backside-Contact cell efficiency could go from 22% to 23.5% just by suppression of the edge losses, a significant 6.8% relative improvement. Considering this result, it appeared that the most important design and/or process improvement was to suppress the edge recombination. Several approaches were studied including edge passivation, perimeter width optimization, shingling the cells, and optimization of the doping level of the substrate.

2.1 Edge passivation

This first solution to the edge loss is obvious but very difficult to implement in the process. The passivation of the edge of the cell has to be done after the cell is completely finished, including anti-reflection coating, metallization, and after the cell is sawed out of the wafer. The passivation process has to be done at low temperature (below 400°C) and in a non-aggressive environment for the finished cell. We investigated several techniques including anodic or chemical oxidation of silicon, low temperature plasma enhanced CVD or evaporation of a passivating dielectric layer. At this time, we have not found a practical technique to passivate the edge of the cell that results in a significant improvement in efficiency. More work has to be done in this area.

2.2 Optimizing the perimeter border width

The distance between the edge of the cell and the edge of the diffused emitter region is a very important parameter that needs to be optimized. In this region, the photogenerated carriers have a greater chance to recombine at the edge of the cell than to be collected by the emitters. In the region where the interdigitated N and P emitters are located, the carrier density is mostly uniform because of the very long diffusion length. Due to the high recombination rate at the edge of the cell (saw cut), the carrier density decreases to the equilibrium carrier density and the carrier density gradient is representative of the recombination current towards the edge of the cell (see Fig. 2).

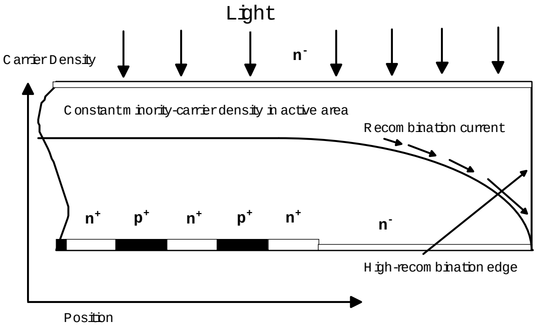

Fig. 2: Edge recombination current in a high-resistivity Backside-Contact solar cell.

One can easily demonstrate [4] that the optimum perimeter width corresponds to a width where the photogenerated current in this region is exactly equal to the edge recombination current. Indeed, if the perimeter region is larger than the one that supplies the recombination current to the edge, it also supplies, although less efficiently than the main part of the cell, a photogenerated current to the emitter. The increase in voltage that results is negligible compared to the loss in collection efficiency. On the other hand, if the perimeter region is smaller, there is an additional carrier recombination current supplied by the main part of the cell, which results in a lower voltage and a lower current.

Assuming a N-type low resistivity substrate in low level injection, the edge recombination current I_r is:

$$I_r = -q\, D_p \frac{dp}{dx}\, P\, W = J_{sc}\, P\, (d-x) \qquad (1)$$

where P is the perimeter length, W the thickness of the cell and d the width of the perimeter region. The integration of equation (1) gives:

$$q\, D_p\, p_{mp}\, P\, W = ½\, J_{sc}\, P\, d^2 \qquad (2)$$

where p_{mp} is the hole density in the main part of the cell under the maximum power condition and is equal to:

$$p_{mp} = \frac{n_i^2}{N_D}\, e^{(qVmp/kT)} \qquad (3)$$

Therefore, the optimum perimeter region width d is:

$$d = \sqrt{\frac{2\, q\, D_p\, p_{mp}\, W}{J_{sc}}} \qquad (4)$$

We have to note that, in case of high injection, the factor 2 in equation (4) becomes a factor of 4, and that equation (3) becomes:

$$p_{mp} = n_i\, e^{(qVmp/2kT)}$$
(5)

Assuming a high-resistivity substrate (in high-injection) of 160 µm in thickness and under one sun AM1.5 illumination, at the maximum power point (Vmp = 580 mV), the carrier concentration is about 10^{15} cm^{-3}. Then the optimum perimeter width is about 600 µm.

2.3 Shingling cells in a module

Assuming that perimeter border area is not illuminated, then the optimum width is as large as possible (in practice, it does not need to be greater than 2 or 3 times the diffusion length). This means that edges are moved far from the active area (for example on one or two sides of the cell) and cells are shingled in the module such that these borders are shadowed. This solution has been proposed earlier [4] and has been effectively used in the modules made by Honda with the PERL cells from UNSW. However, it has many drawbacks such as the difficulty of making such modules, the shadowing loss at oblique incidence of light, the increased thickness of the module and the risk of reduced reliability. We did not choose this solution because it was not acceptable to the customer.

2.4 Optimizing the doping level of the substrate

Considering equations (3) and (4), it appears that the carrier concentration at the maximum power point, the perimeter width and the edge recombination current would all be reduced , by using a doped substrate (or lower resistivity). For both N- and P-type substrates, an optimum doping level as shown on Figure 3 is around 10^{16} cm-3. Above this value, the lifetime in the bulk and the efficiency are reduced. At high doping levels, the minority carrier density is suppressed so much that the gradient from the front to the back of the solar cell becomes greater than the absolute minority carrier density and the operation of the Backside-Contact solar cell suffers. This effect is described in detail in [7].

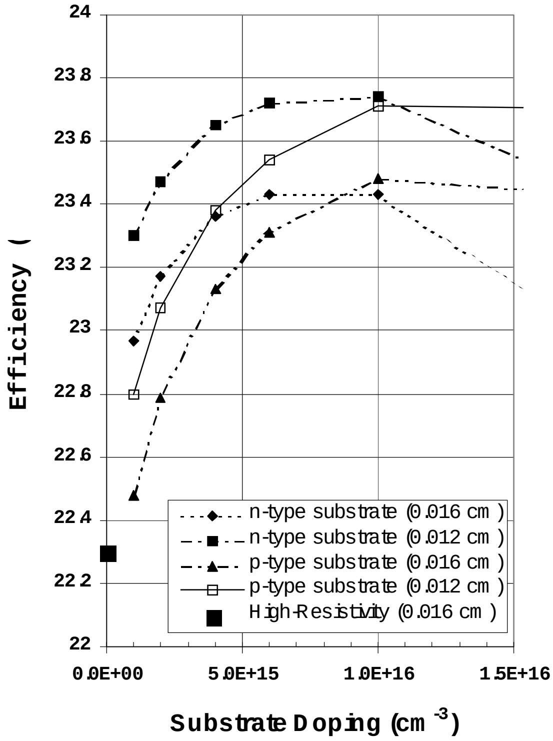

Fig. 3: Efficiency of Backside-Contact cells vs. Substrate doping level for N and P-type substrates, and for 120 µm and 160 µm thick cells.

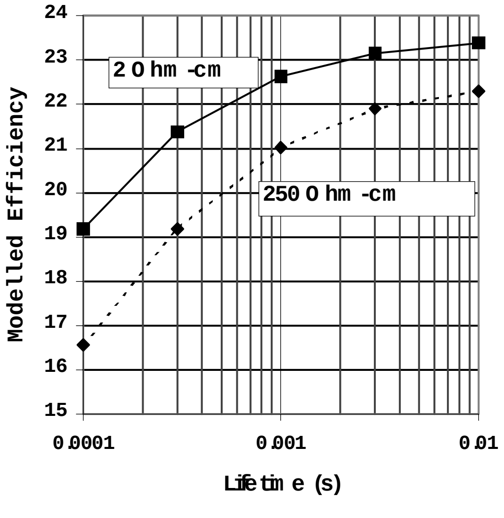

Fig. 4: Influence of carrier lifetime on the efficiency of Backside-Contact cells for low- and high-resistivity silicon substrates.

Assuming that the maximum power point voltage is about 580 mV, the optimum perimeter width for a N-type substrate with a doping level of 10^{16} cm^{-3} and a thickness of 160 µm is 140 µm, and the edge recombination current is reduced by a factor greater than 4 compared to undoped substrates. Obviously, the carrier lifetime varies drastically with the substrate doping level. For example, the usual guaranteed carrier lifetime for a high-resistivity FZ substrate is 1 msec, but the typical value is around 5 msec. For low resistivity material, although the wafer manufacturer does not guarantee the carrier lifetime, a carrier lifetime of 0.9 msec for 10^{16} cm^{-3} N-type FZ wafers has been measured. Figure 4 shows the cell efficiency of 250 Ω.cm and 2 Ω.cm wafers as a function of lifetime. It shows that the 2 Ω.cm cell will always have a higher efficiency than the 250 Ω.cm cell if the carrier lifetime is greater than 0.7 msec. Being conservative, we decided to used 2.2 ± 0.7 Ω.cm N-type substrates for only part of the solar cell production. The corresponding doping level is 2.1 10^{15} cm^{-3}, and a typical measured carrier lifetime is around 1.5 msec.

3. MANUFACTURING OF HIGH-EFFICIENCY CELLS

SunPower's Backside-Contact cells partially powered two cars during the '96 World Solar Challenge: the Team California car (Stanford and Berkeley), which had about 4 m^2 of high-efficiency Backside-Contact solar cells, and Honda's spare car which was fully covered (12 m^2) by SunPower's cells but did not race. Also, Honda's racing car had is canopy covered with Backside-Contact cells. Cells of two different dimensions were fabricated: 64.3 x 32.9 mm and 32.15 x 32.9 mm, yielding either 2 or 4 cells per 100 mm silicon wafer. About 80% of the starting material was 250 ± 50 Ω.cm FZ N-type silicon, the remaining 20% was 2.2 ± 0.7 Ω.cm material. The thickness of the cell was 160 µm. The manufacturing production of a total of 10,000 cells of 21.15 cm^2 had a duration of 6 months and the production rate was around 500 cells per week.

4. RESULTS

Figure 5 shows the efficiency distribution of the '96 Race Cell production compared to the '93 production. The histogram includes cells made from 250 Ω.cm and from 2.2 Ω.cm material. The mode of the distribution was 21.2%, a 1% absolute boost over the '93 efficiency distribution. The maximum measured efficiency was 23.2%. Considering a batch of about 5000 cells fabricated at the same time (1,135 cells of 2.2 Ω.cm and 3,985 cells of 250 Ω.cm), the efficiency distribution shown in Figure 6 demonstrates that the cells made with the low resistivity material have higher efficiencies by about 0.4% absolute. More than 85% of the 2.2 Ω.cm cells were greater than

22% efficient, compared to only 64% of the 250 Ω.cm cells. The respective modes are 22.7% and 22.3%.

It is important to comment that the cell design, particularly the perimeter region width, was optimized for 250 Ω.cm substrates and not for 2.2 Ω.cm substrates. It is expected that the low-resistivity efficiency distribution would have been boosted by another 0.8% absolute if the perimeter width were decreased to the optimum, if the cell geometry were re-optimized for doped substrates, and if the carrier lifetime in the doped material were in fact 5 msec, as modeled. Since, we had much more high-resistivity material, we optimized the design for these wafers.

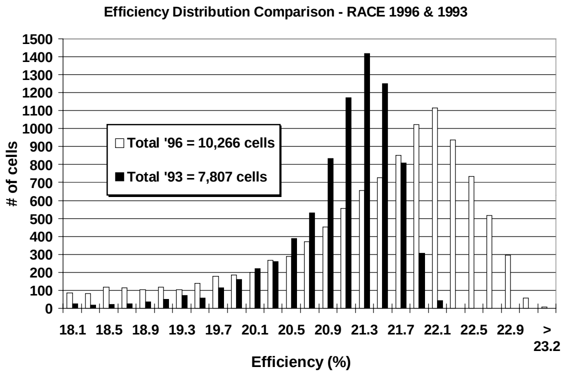

Fig. 5: Efficiency distribution of Race Cell production for 1993 and 1996 World Solar Challenge.

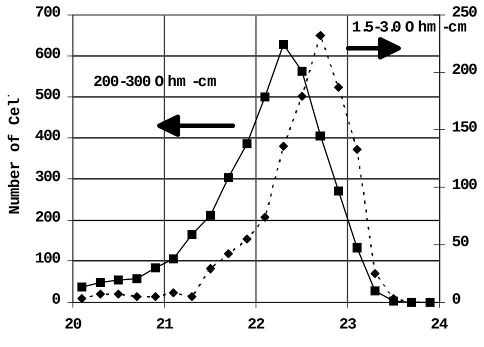

Fig. 6: Efficiency distribution of 5,120 Backside-Contact cells, 1,135 low-resistivity and 3,985 high-resistivity

Table I

Characteristics of 21.15 cm^2 Backside-Contact solar cells measured at Sandia and Fraunhofer Institute (FhG)

	Isc (A)	**Voc (V)**	**FF**	**Effic. (%)**	**Spect.**
Sandia	0.832	0.681	0.82	22.1	AM1.5
FhG ISE	0.846	0.681	0.833	22.7	AM1.5
FhG ISE	1.028	0.686	0.83	20.3	AM0

Several cells were independently measured at Sandia National Labs and Fraunhofer Institute. The results are reported in Table I. Since the high-efficiency Backside-Contact cells are also intended to be used on high-altitude solar airplanes, one of the cells was measured under the AM0 spectrum at Fraunhofer Institute. A 20.3% AM0 efficiency has been reported. This latter result shows that the Backside-Contact cell is one of the most suitable cells for solar airplanes.

5. CONCLUSIONS

The efficiency of Backside-Contact cells for one-sun, high-value applications, has been improved by reducing the edge recombination losses. We demonstrated that the use of low-resistivity substrates can effectively reduce the edge recombination loss and boost the efficiency of Backside-Contact cell by at least 0.4% absolute. We expect in the future to continue to improve the efficiency with a full optimization of the cell for low-resistivity substrates, and by developing a method to passivate the edge of the cell. The '96 Race Cell production yielded an AM1.5 efficiency distribution between 20% and 23.2%, the mode being 22.1%, demonstrating a 1% absolute boost over the '93 Race Cell production. More than 85% of the low-resistivity cells were greater than 22% efficient. Independently confirmed efficiencies of 22.7% under AM1.5 and 20.3% under AM0 spectrum at 25ºC have been demonstrated.

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